The Dissertation Committee for Wai Kiong Chong
Certifies that this is the approved version of the following dissertation:

CONSTRUCTION PRODUCTION RATE INFORMATION SYSTEM FOR HIGHWAY PROJECTS

Committee:

James T. O'Connor, Supervisor

John D. Borcherding

Carl T. Haas

Ellen M. Rathje

Daniel Powers

CONSTRUCTION PRODUCTION RATE INFORMATION SYSTEM FOR HIGHWAY PROJECTS

by

Wai Kiong Chong, B.S., M.S.

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

The University of Texas at Austin

May, 2005

To

my wife, Yvonne Lai

whose dedication in her work inspires me

Acknowledgements

I would like to express my deepest appreciation to my supervisor, Dr. James T. O'Connor for his excellent support, invaluable guidance, and patience. Without him, this dissertation would not have been completed. Throughout the research experience, Dr O'Connor has taught me a great amount about research and attitudes. I'm greatly indebted to him.

My special thanks are also extended to my advisory committee members, Dr. John D. Borcherding, Dr. Carl T. Haas, Dr. Ellen M. Rathje, and Dr. Daniel Powers, for their invaluable advice and words of encouragement. In addition, I would like to thank the Project Monitoring Committee members of the TxDOT Research Project 0-4416 for their assistance on this study.

I would also like to thank Shiv Ranadaran, who retired from TxDOT on November 21, 2004, for his tremendous amount of effort in helping me obtain additional data even after the end of the research project. I would also like to thank Dr Sang-Hoon Lee from the University of Houston for giving me valuable advice on disruption analysis methodology.

I'd like to thanks Dr Yao-chen Kuo and Dr Young-ki Huh, my two research partners, for all the fun during our research trips!

CONSTRUCTION PRODUCTION RATE INFORMATION SYSTEM FOR HIGHWAY PROJECTS

Publication No. ______________________

Wai Kiong Chong, Ph.D.
The University of Texas at Austin, 2005

Supervisor: James T. O'Connor

The primary objective of this research study was to develop an improved production rate information system that incorporates production drivers. The improved production rate information system is intended to improve the accuracy of construction contract time determination for highway construction projects and to ease the estimation process. Foundation, sewerage and pre-cast retaining wall structures often lie on the critical path and the production rates and "drivers" of the production rates for these activities were examined for statistically significant relationships. Production rates affected by disruption(s) were also measured and relationships were modeled so that production rates could be properly adjusted. An user-friendly system, called the Highway Production Rate Information System (HyPRIS) was developed using Visual Basic.

Table of Contents

LIST OF TABLES xv

LIST OF FIGURES xix

CHAPTER 1: INTRODUCTION **1**

1.1 Research Background and Motivation 1

1.2 Research Objectives 4

1.3 Overview of Study Methodology 5

1.4 Data Collection Methodology 8

1.5 Structure of Dissertation 9

CHAPTER 2: RESEARCH METHODOLGY **10**

2.1 Literature Review 11

2.2 Contract Time Determination System 13

2.3 Historical Records 16

2.4 General Factors Affecting Productivity 16

2.5 Weather 18

2.6 Scheduled Overtime 19

2.7 Disruptions 21

2.8 Congestion and Accessibility 24

2.9 Region 25

2.10 The Effects of Learning and Learning Curve 26

2.11 Rainfall 26

2.12 Advancement in Technology 27

2.13 Traffic 28

2.14 Methods of Productivity Analysis 29

2.15 Other Factors Affecting Production Rates 30

2.16 Conclusion to Literature Review 30

2.17 Factors chosen by the research 31

2.18 Data Collection Tools 32
2.19 Job Site Selection 35
2.20 Site Visitations and Data Validation 35
2.21 Summary of Data Collection Process 37
2.22 Rationale for Production Rate Computation 38
2.23 Correction for Delays and Crew Size 39
2.24 Alternative Data Sources for Delay Modeling 40
2.25 Statistical Methods of Data Analysis 41
2.26 Conclusion 49

CHAPTER 3: DATA ANALYSIS: DESCRIPTIVE STATISTICS AND COMPARISON WITH CONTRACT TIME DETERMINATION SYSTEM 51

3.1 Site Observation Data 51
3.2 As-Built Data 54
3.3 Differences Between CTDS and Observations 55

CHAPTER 4 : ANALYSIS OF DRIVERS 68

4.1 Identifying Significant Drivers and Establishing Relationships 68
4.2 Analysis by Work Item 69
4.3 Multiple Regressions 94
4.4 Summary of Drivers and Formulas 99
4.5 Predicting Production Rates Using the Drivers and Formulas 101
4.6 Impact of Disruption on Production Rates 104

CHAPTER 5 : HIGHWAY PRODUCTION RATE INFORMATION SYSTEM 115

5.1 Information Identification for HyPRIS 115
5.2 HyPRIS Framework 117
5.3 HyPRIS Design — Support Functions 126

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS 129

6.1 Summary 129

6.2 Recommendations 130
APPENDIX A QUESTIONNAIRE FOR SELECTING WORK ITEM………………. 133
APPENDIX B RESULTS OF THE SURVEY FOR SELECTING WORK ITEMS….. 137
APPENDIX C PRODUCTION RATE TRACKING (PROJECT LEVEL)…………… 138
APPENDIX D PRODUCTION RATE TRACKING: WORK ZONE LEVEL………..140
APPENDIX E PRODUCTION RATE TRACKING: WORK ITEM LEVEL………... 142
APPENDIX F TRACKING CALENDAR……………………………………….. 144
APPENDIX G WORK ITEM SHEETS…………………………………………. 146
APPENDIX H SAFETY PROTOCOL…………………………………………... 153
APPENDIX I MANUAL FOR USING HYRPIS…………………………………155
APPENDIX J MANUAL FOR UPDATING HYPRIS…………………………….. 158
APPENDIX K SURVEY ON CTDS USAGE AND IMPORTANCE………………... 159
APPENDIX L Q-Q PLOT FOR DATA POINTS…………………………………163
References 169
Vita 177

List of Tables

Table 1.1: Types of Work Items Selected 7

Table 2.1: Factor definitions (Ovararin and Popescu (2001) 24

Table 2.2: Proposed project level factors 31

Table 2.3: Proposed work item level factors 32

Table 2.4: Proposed work zone level factors 32

Table 2.5: Rationale for Production Rate Computation 38

Table 2.6: Crew Work Day Computation - Half-Day Rule 39

Table 2.7: Sample Sizes & No. of Predictor (Green, 1991) 46

Table 3.1: Schedule of Site Visits 51

Table 3.2: Consolidated Data Points 53

Table 3.3: Units Adopted - CTDS versus Research 56

Table 3.4: Scope Differences - CTDS vs Research 57

Table 3.5: Adopted units – CTDS vs Research 59

Table 3.6: Production Rates - CTDS vs Observations 65

Table 3.7: Production Rates - CTDS vs As-builts 66

Table 3.8: Production Rates - As-builts vs Observations 66

Table 4.1: Work Items and Drivers Relationships Findings 70

Table 4.2: Drivers' redefined 71

Table 4.3: Summary of Formulas and Ranges of Application 99

Table 4.4: Summary of Drivers of CTDS and Research 100

Table 4.5: Discrete Drivers and Range of Production Rates 102

Table 4.6: Formulas and Application for Multiple Regressions 103

Table 4.7: Production recovery on different clay content 108

Table 4.8: P-values for soils with different clay content.......................... 109

Table 4.9: P-values between soils different clay content 109

Table 4.10: Production losses over three recovery days 114

Table 5.1: Media and Software used in HyPRIS....................................... 128

List of Figures

Figure 1.1: Data Collection Process 8

Figure 2.1: Information Sources from Hancher et al. (1992) 12

Figure 2.2: Factor Model (Thomas and Yiakoumis 1987) 17

Figure 2.3: Effects on productivity from Otime Work (BRT, 1980)............ 20

Figure 2.4: Structure of Factors Analyzed.. 37

Figure 2.5: Annotated Sketch of the Box Plot 42

Figure 2.6: Flow Chart of Driver Analysis 44

Figure 2.7: Research Methodology... 50

Figure 3.1: Box plots — Drilled Shaft Foundation (lf/Crew Day)............... 61

Figure 3.2: Box plots — Piling Foundation (lf/Crew Day).......................... 62

Figure 3.3: Box plots — MSE Wall (sf/Crew Day) 62

Figure 3.4: Box plots — RCP (lf/Crew Day) 63

Figure 3.5: Box plots — PCB (cy/Crew Day)... 63

Figure 3.6: Box plots — CIP Box Culverts (cy/Crew Day) 64

Figure 3.7: Box plots — Inlets and Manholes (ea./Crew Day) 64

Figure 3.8: Box plots — Head Wall/Wing Wall (sf/Crew Day) 65

Figure 4.1: Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster].. 73

Figure 4.2: Prestressed Concrete Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster] for Small Pile Cluster............74
Figure 4.3: Drilled Shaft Foundations: Scatterplot [vs. Total Length of Shafts (lf) in Cluster]............76
Figure 4.4: Drilled Shaft Foundations: Scatterplot (vs. Location of Operation)............77
Figure 4.5: Drilled Shaft Foundations: Scatterplot (vs. Total Number of Shafts in Cluster)............79
Figure 4.6: Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Size of Wall (sf)]............80
Figure 4.7: Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Wall Coping Length (lf)]............81
Figure 4.8: Precast Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]............83
Figure 4.9: Precast Box Culverts: Scatterplot (vs. Soil Types)............84
Figure 4.10: Precast Box Culverts: Scatterplot (vs. Clay Content on Work Zone)............85
Figure 4.11: Cast in Place Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]............86
Figure 4.12 Reinforced Concrete Pipe: Scatterplot and Regression Results [vs. Length of Pipe Run (lf)]............87

Figure 4.13: Reinforced Concrete Pipe: Scatterplot (vs. Orientation of Line)88

Figure 4.14: Reinforced Concrete Pipe: Scatterplot (vs. Work Zone Accessibility) 89

Figure 4.15: Inlets and Manholes: Scatterplot [vs. Total Quantity (ea.) for Line] 91

Figure 4.16: Inlets and Manholes: Scatterplot (vs. Inlets or Manholes for Line) 92

Figure 4.17: Inlets and Manholes: Scatterplot (vs. Cast in Place or Precast) . 93

Figure 4.18: Head Walls/Wing Walls: Scatterplot [vs. Wall Surface Area (sf)] 94

Figure 4.19 Production rate estimation process 104

Figure 4.20: Recovered production on first day 111

Figure 4.21: Recovered production on second day 111

Figure 4.22: Recovered production on third day 112

Figure 4.23: Recovered production on fourth day 112

Figure 4.24: Average recovered production for first three days 113

Figure 5.1 HyPRIS Structure 116

Figure 5.2 HyPRIS Main Frame 118

Figure 5.3: Work Item Division, First Window 119

Figure 5.4: Work Item Numbers Window 120

Figure 5.5: Work Item (RCP) Main Frame 121

Figure 5.6: Frame for Line Orientation 122

Figure 5.7: Box Plot for RCP.. 123

Figure 5.8: Source Data for RCP 124

Figure 5.9: Window for Work Item Description 125

Figure 5.10: Glossary Table... 126

CHAPTER 1: INTRODUCTION

1.1 RESEARCH BACKGROUND AND MOTIVATION

Construction time estimation at the design stage is an important project management process. Even with today's technology, highway construction delays are still very common and pose a serious threat to on-time project completion. Any delays lengthen project completion time and inconvenient period to road users, residents and businesses operating around the highway project.

Construction time estimation at the design stage has been a mixture of experience and speculation. The methods adopted by contractors and designers are different and thus contractors often complain that designers do not provide sufficient contract time and designers often blamed contractors for delays. On the other hand, road users and residents often complain that highway construction taken too much time. Many residents also complain of road closure when no construction work is being carried out.

Disruptions to normal life and traffic are part of any highway construction project. Overestimated project time lengthens the inconvenience period to businesses, residents, and road users, while underestimated project time increases risks of delay and disputes. Improving designers' accuracy for construction time estimates can help reduce the possibilities of disruptions, shorten the period of inconvenience, and reduce the risks of disputes.

Most design agencies rely heavily on the experience of their senior staff to work out project time at the design stage. Some agencies, like the Texas Department of Transportation (TxDOT), have some production rate support information. Planning engineers in Texas Department of Transportation (TxDOT) have relied upon TxDOT's Contract Time Determination System (CTDS; Hancher, et al. 1992) and RS Means for such information. In general, planning engineers seek durations that are achievable but not too loose (i.e., over-length in duration).

Though RS Means is primarily a cost estimation tool, its rates have been used regularly by planning engineers to work out meaningful production rates. The information provided by CTDS includes production rates and some associated factors for selected work activities. Planners can adjust the provided rates with the factors in order to obtain more realistic and accurate rates when certain project conditions apply. CTDS production rates were based on survey inputs gathered from site personnel and planning engineers and not from field data. However, there have been concerns about the reliability or accuracy of the CTDS production rates, and many planners have resorted to relying solely on their own experience for determining activity durations. Current highway construction time estimation is based primarily on construction experts' experiences and "best guesses," often with little formal and objective analysis. Little research has been attempted to provide industry with reliable production information. Many published papers in the field of productivity focus on project performance evaluation or cost control rather than on time estimation. Furthermore, studies that deal with the aforementioned factors are often based on data from completed projects or surveys, and so their accuracy is questionable.

This research looks at two major areas in construction production rate estimation. The first includes improving the quality of information so that production rate estimation can be more accurate and reliable. The second looks at production rate adjustments at the construction stage. Such adjustments can help align the estimated production rates at the design stage to more realistic rates that are affected by construction disruptions.

As an initial step, researchers investigated the current usage level of and satisfaction with the CTDS among TxDOT's various districts. The results of the multi-district survey are presented in appendices. A key conclusion of the survey was that TxDOT needed a new, more accurate alternative to CTDS.

Thus, highway construction time estimation continues to be a challenge despite efforts by industry and academia. High production rate variance is the key challenge. It is widely recognized that production rates are affected by many factors such as weather, project type, site conditions and terrain, influence of the learning curve, and so forth. Such factors can either speed up or slow down the production of an activity. Thus, realistic production rates are needed in order to develop accurate construction time estimates, and thorough consideration of the factors affecting production rates is also important for accurate time estimation. As Herbsman and Ellis (1995) noted, "a scheduler has to consider a wide range of factors likely to affect highway project duration."

As a result, research was carried out to measure actual field production rates, to determine those factors that affect field production rates, and factors that cause disruptions. The new information system resulting from this investigation, which is described in this report, includes production rates for many selected work items that normally lie on the critical path and quantified relationships with various production rate factors.

1.2 RESEARCH OBJECTIVES

The intention of this research was to develop a highway production rate information system which designers can use to estimate construction duration at the design stage. Three Graduate Research Assistants have been assigned to this task and each assistant is given a certain set of work items. The work presented in this dissertation covers nine different work items. The work items include, drilled shaft foundations, pre-cast concrete piling foundations, pre-cast concrete box culverts, cast-in-place concrete box culverts, pre-cast reinforced concrete pipes, headwalls and wingwalls, inlets and manholes and mechanized stabilized earthwall. Four specific research objectives were established:

(1) Collect accurate information on production rates and productivity drivers such that this information could be used to develop the system.

(2) Select and use appropriate statistical methods to hypotheses and test relationships between production rates and drivers.

(3) Select and use appropriate statistical methods to quantify impacts of construction delays and develop production rate adjustment models.

(4) Develop a production rate information system that contains needed information for time estimation.

1.3 OVERVIEW OF STUDY METHODOLOGY

1.3.1 Scope Limitations

There are three parts in this research. The first is to develop a highway production rate information system that can be used at the design stage. The second part focuses on adjusting the preliminary production rates for delays and disruptions during the construction stage. The third examines the various requirements of the information inputs for the production rates information systems and discusses design of the system. The production rates mentioned here are limited to foundation, storm sewers and pre-cast retaining wall for highway projects, with a total of 9 work items. These work items include piling foundations, drilled shaft foundation, small sized reinforced concrete pipes (RCP), large sized reinforced concrete pipes (RCP), pre-cast concrete box culverts, cast-in-place concrete box culverts, wing-walls/head-walls, inlets & manholes, and mechanically stabilized earth wall (MSE Wall). The usage of the system is also limited to the design stage of schedule preparation.

1.3.2 Scope of Data Collection

Critical work items from foundation, pre-cast retaining wall and storm sewers that were most commonly found on Texas highway projects were selected. These work items include drilled shafts and piling foundations, Mechanical Stabilized Earthwall (MSE Wall), reinforced concrete pipes (RCP), pre-cast and cast-in-place concrete box culverts (PC Box, CIP Box), head walls and wing walls, and inlets and manholes. The study was only carried out on critical work items as these work items drive both project durations and schedules. There would be sufficient time float time for the non-critical work items and these non-critical work items can easily fit into the schedules with minimal impacts to the project durations and schedules. The questionnaire used for the study is documented in Appendix A and the result of the survey is documented in Appendix B.

Next, productivity factors that are perceived to be important to construction time estimation at the design stage were selected. These factors were gathered from a series of literature reviews, discussed above, inputs from TxDOT Engineers and from the authors' experiences. However, certain factors surfaced during the data collection process and the data collection tools that incorporated these factors and previous data points were adjusted accordingly.

Representative highway construction projects were selectively chosen and data were only collected from these projects. Several projects were also chosen to verify the analyzed data. Projects that were not representative of the project types and had production rates that seemed to be outliers were eliminated. The collected data were further scrutinized using statistical techniques to further eliminate statistical outliers.

Since the research looks at production rates estimation at the design stage to aid construction, the scope of data collection includes: (1) a range of production rates for all the investigated work items, (2) an estimation formula for determining production rates caused by different factors, (3) a range of production rates for different factors and (4) daily production and factors that affect each daily production.

1.3.3 Work Items Selection

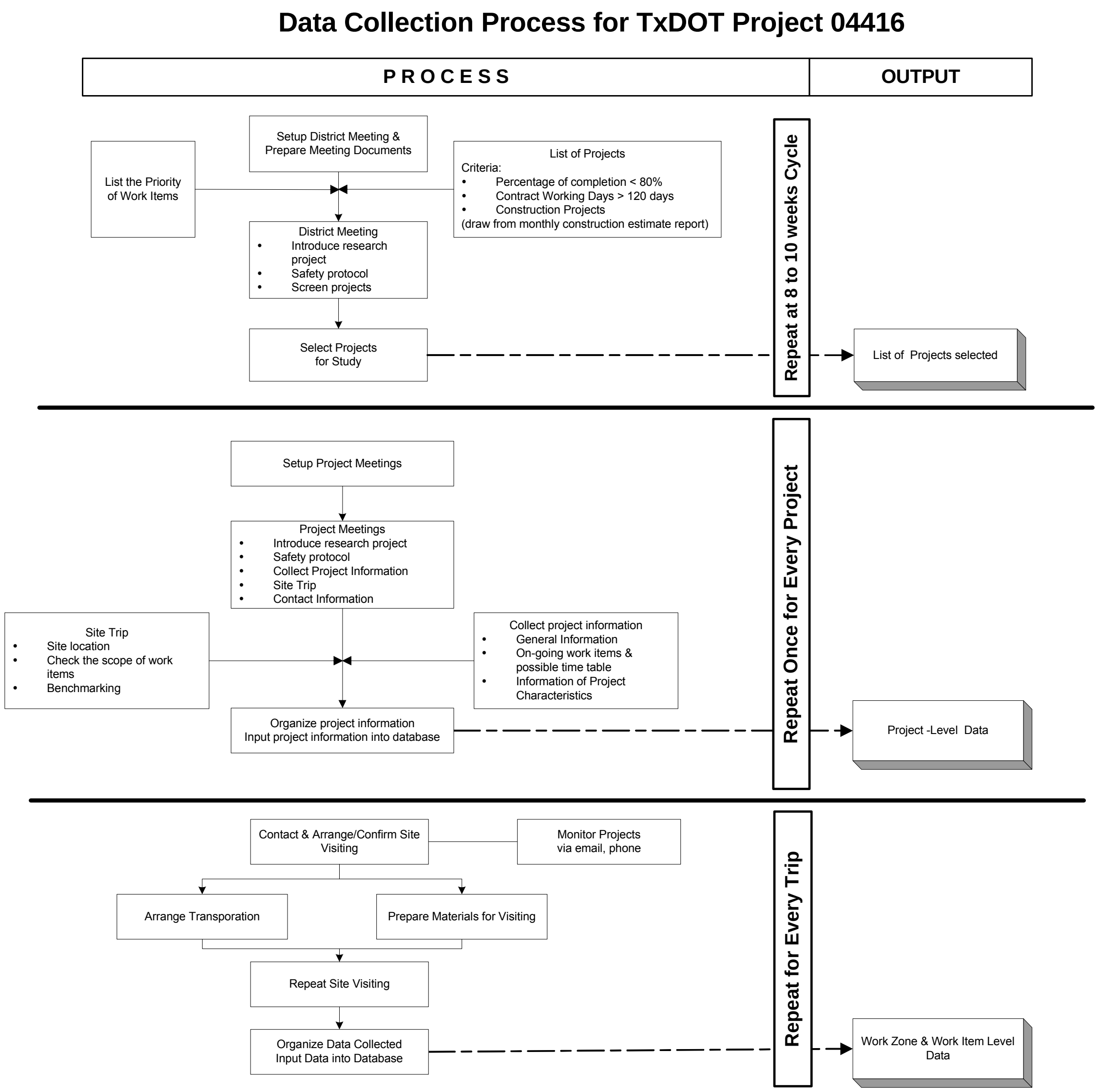
A highway construction project usually involves hundreds of work items. Some of them fall more frequently on the critical path; these items usually affect contract time, whereas other work items do not affect the overall time of construction. Through survey and rigorous discussion were carried out earlier on in the research, the priorities of these work items were identified. Survey participants were selected by the Project Monitoring Committee (PMC) for TxDOT Research Project 0-4416. The results from the survey and discussions showed that there were two foundation work items, one retaining wall work item and six storm sewers work items that were considered critical to most project schedules. These work items were selected for the research. The following table listed these work items and the number which TxDOT uses to identify them.

Table 1.1: Types of Work Items Selected

<table>
<tr><th colspan="2">Item No.</th><th>Item Description(s)</th></tr>
<tr><td colspan="2">409</td><td>Prestressed concrete piling</td></tr>
<tr><td colspan="2">416</td><td>Drilled shaft foundations</td></tr>
<tr><td colspan="2">423</td><td>Retaining wall — MSE wall</td></tr>
<tr><td rowspan="2">462</td><td>462-1</td><td>Concrete box culverts and storm drains (precast)</td></tr>
<tr><td>462-2</td><td>Concrete box culverts and storm drains (cast in place)</td></tr>
<tr><td rowspan="2">464</td><td>464-1</td><td>Reinforced concrete pipe (18–42 in.)</td></tr>
<tr><td>464-2</td><td>Reinforced concrete pipe (48–72 in.)</td></tr>
<tr><td colspan="2">465</td><td>Manholes and inlets</td></tr>
<tr><td colspan="2">466</td><td>Head walls and wing walls</td></tr>
</table>

1.4 DATA COLLECTION METHODOLOGY

Figure 1.1: Data Collection Process



A data collection process plan, shown in the preceding figure, was developed to enhance the effectiveness of data collection. Three cycles were included in this plan. The first consists of the process flows of conducting a district meeting to select projects for data collection; the second involves conducting a project meeting to kick off the data collection in a project; the third, the regular collection of project data at the construction site.

1.5 STRUCTURE OF DISSERTATION

In the subsequent chapter, literature on relevant topics is reviewed and statistical techniques applied in this research are discussed. Chapter 3 includes discussions on research objectives, purposes, and methodologies, along with detailed analyses of the differences between CTDS production rates and those developed by this research. Chapter 4 presents in detail the relationships between work item production rates and significant drivers, along with formulas for modeling such relationships. Chapter 4 also presents the results from multiple regression analyses of some of the work items. Chapter 5 discusses the development of the Highway Production Rate Information System and how TxDOT planners can use the system to determine construction duration at the design stage. Chapter 6 concludes the research by providing guides on the applications of the models and provides some recommendations for future research.

CHAPTER 2: RESEARCH METHODOLGY

Accuracy and reliability of information is vital to the research. Research found that most of the inaccuracies of the production rates estimation systems lie within the sources of information. Inaccurate information feeding into the systems will result in inaccurate outputs from the systems. Thus, data were collected from field operations and the sources of these data included foremen's diaries, reliable data input systems and the short-term memories (up to two weeks) of the foremen and project managers. Daily site occurrences were tracked on a weekly basis.

A data collection technique and tool was also developed to help gather the field-based information more efficiently and accurately. Such information would be used to test the relevance of the Contract Time Determination System (CTDS) and to improve the existing structure and information in the CTDS (e.g., field production rates and factors driving these production rates) and to develop appropriate models for production rates estimation and delaying effects on production rates. The data collection technique included a series of data collection tools, each tool aims at collecting information from different aspects of the field operations. In addition, literature was reviewed to further identify other common drivers of production rates that are most useful to designers. Information that the Texas Department of Transportation (TxDOT) found useful to the production rate estimation process were also identified and incorporated into these data collection tools.

Relevant projects located in the state of Texas are specifically selected to ensure uniformity and reliability of data. Projects that were most frequently built by TxDOT were selected to ensure that data would not be biased.

Appropriate methods for analyzing these data were also selected, based on the needs of the research and the arrangement of the data. Linear and nonlinear regressions analysis, *t* tests, and regression modeling were preliminarily chosen. Using the analyses in this plan, production rates models could be developed for the nine selected work items. Finally, an user-friendly information system would be developed to allow the analyzed information to be utilized more productivity.

2.1 LITERATURE REVIEW

The Transportation Research Board conducted a series of studies in 1981 and 1995 to investigate and develop systems that could be used to estimate contract time for highway construction projects (NCHRP 1981; Herbsman et al. 1995). Conclusions indicated that "realistic production rates are the key in determining reasonable contract times" (Herbsman et al. 1995).

Developing scheduling networks is a complicated and time-consuming task. Hancher et al. (1992) highlighted several methods employed. A survey conducted in Hancher et al. (1992) surveyed participants from thirty-six departments of transportation (DOTs) highlighted the fact that personnel determining contract time relied heavily on personal experience. Figure 2.1 shows the results of the survey. Forty-four percent of the respondents relied on personal experience to estimate production rates, 30 percent used standard production rates that were usually provided by the DOTs, and 22 percent used production rates from historical records of previously completed projects.

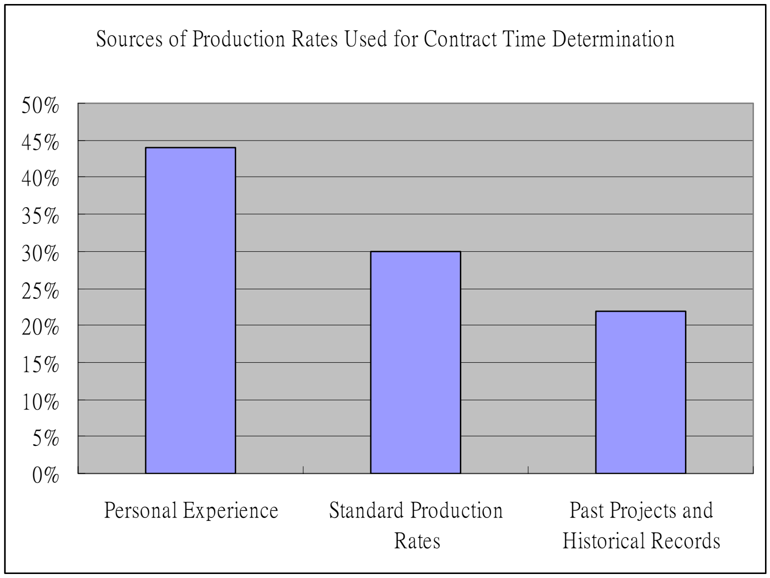


Figure 2.1: Information Sources from Hancher et al. (1992)

Production rates obtained from personal experience and historical records were usually not properly appraised and thus were often unreliable. Essential tools and information, such as consideration of production rate drivers, were often lacking. As a result, personnel who developed the project time estimation generally assumed a single representative production rate for all work items in the entire project. Once the production rate was established, inaccuracies would often be amplified when it was applied throughout the project. Rather than relying on experience or improperly appraised historical records, this research has attempted to quantify the impact of production drivers and to remove unreliable sources that would lead to inaccurate time estimates.

2.2 CONTRACT TIME DETERMINATION SYSTEM

The CTDS is "a conceptual estimating system for predicting contract time for highway construction projects and is not to be used for the detailed planning of actual construction activities for a project" (Hancher et al. 1992). This system is a product from a research study conducted by the Texas Transportation Institute and the TxDOT in 1992. Part of that project's objective was to explore production rates of different work items that are commonly used in highway construction. Survey forms were sent to participants in twenty-five TxDOT districts. The survey form was used to investigate the daily production rates of the forty-two most common work items found in the highway projects constructed by TxDOT. The participants were asked to evaluate the impact of the five production drivers, namely, *location*, *traffic conditions*, *complexity*, *soil conditions*, and *quantity of work* on each of the work items. Participants who completed the survey were required to estimate the low, average, and high production rates for each of the work items and to determine whether the drivers had any significant impact on the production rates. In addition, a request form was sent to all the transportation agencies in the forty-nine states to request similar production rate data. Twenty-four states responded. A production rate database was developed from the responses of the survey from these transportation agencies.

The CTDS database consists of three values of production rates (low, mean, and high) for forty-two work items, five production rate drivers, and production rate adjustment factors for the drivers. There is no mention about how weather is treated in the CTDS.

A survey on CTDS usage and importance was conducted during the earlier part of this research. The survey concluded that many TxDOT districts did not use CTDS and would not increase CTDS usage in the future. The detail results are documented in Appendix K. 12 districts did not use CTDS at all, 10 districts used CTDS in less than 25% of their projects while only 6 districts used CTDS in more than 25% of their projects.

The survey also highlighted five major areas of complaints that could be used to develop an alternative to CTDS.

a. System is inflexible, not user-friendly and requires extensive training:

The complaints about the system include:

(1) CTDS is unable to integrate with other software that planners are more familiar and as a result they either have to abandon using the system or live with CTDS

(2) CTDS requires training, if not, it appears to be non user-friendly and the training is quite extensive. However, planners still prefer to use Primavera and other software as those systems are more flexible and useful

(3) CTDS is inflexible and planners have to redo entire calculations if they find some mistakes in their original calculations. Time is usually wasted in order to repeat the entire process.

(4) Planners prefer to work on platforms and interfaces they are more familiar with (usually refers to MS Windows interface) and CTDS's platforms and interfaces are very different from those of the MS Windows. As a result, planners cannot work efficiently on CTDS.

(5) Finally, users cannot introduce their own formulae and factors which can be more relevant to their projects. This limits the functionality and usefulness of CTDS.

b. There are better alternate systems:

Several districts implement other software to carry out time estimation function. These software include Suretrak, Primavera and MS Project. CTDS cannot match their performance, in term of window interface, user-friendliness and flexibility. As a result, CTDS is often used as a support system to these software. In addition, many districts also highlighted that manual calculations were more accuracy and flexible than using CTDS alone.

c. System updating issues:

CTDS operates on Lotus platform and Lotus is no longer being used as a spreadsheet. As a result, CTDS can no longer be updated and information migration from CTDS to other software is also not possible. Consequently, outdated information on CTDS cannot be modified.

d. Information in the system are not accurate:

TxDOT planners find that the production units, production rates, lead and lag relationships and factors, in the CTDS are not accurate.

e. Information in the system are not comprehensive enough:

Finally, there are many complaints that the information in CTDS are not comprehensive enough. Various districts suggest that CTDS does not contain regional factors, yet CTDS cannot incorporate these factors during calculation process. Consequently, planners in many districts stopped using CTDS totally.

2.3 HISTORICAL RECORDS

Much research has relied on historical records to develop production rates. Such data come in the form of records kept by the contractors or the clients. Although some well-kept records may provide extremely accurate production rate information, there is insufficient information in these records to allow factors and the variability of these factors on production rates to be identified. Moreover, principal contractors do not keep detailed production rate information on some work items, such as drilled shafts, that are carried out by subcontractors. For these reasons, historical records cannot be fully relied upon.

2.4 GENERAL FACTORS AFFECTING PRODUCTIVITY

Many studies have identified productivity factors and measured their effects on productivity. Most of these focused on the identification and quantification of factors that caused losses of construction productivity. Frequently cited factors from these studies include weather, scheduled overtime, disruption, congestion, and region (Halligan 1994; Koehn 2001). This section will review published studies associated with the identification and quantification of productivity factors and disruption effects related to this study.

Thomas and Yiakoumis (1987) employed the factor model to present relationships between labor productivity and productivity factors. The factor model displays the effects of the learning curve and other factors on labor productivity, as shown in the following figure. In the factor model, the ideal productivity curve presents a correlation between the cumulative man-hour per unit of work and the cumulative unit of work in an ideal condition of no disruption. The ideal productivity curve is varied with different crews. Their study indicated that losses in productivity are caused by numerous factors such as environmental factors, site factors, management factors, and design factors.

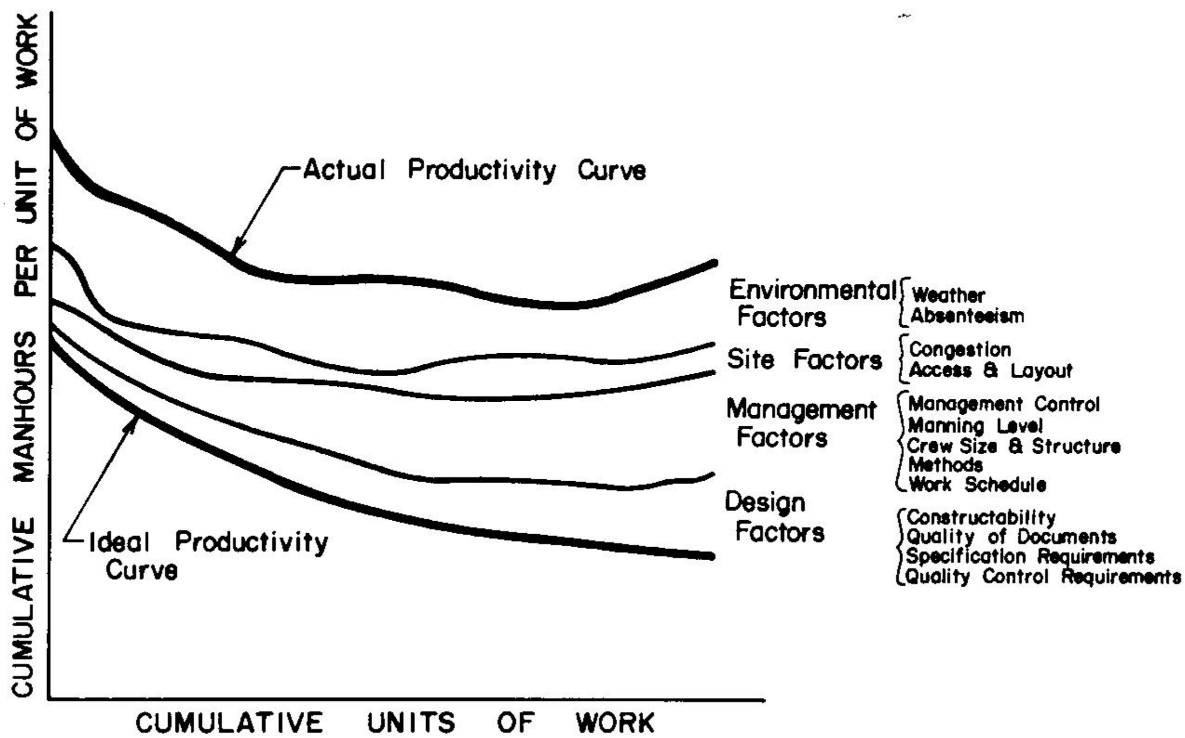


Figure 2.2: Factor Model (adopted from Thomas and Yiakoumis 1987)

Allouche et al (2001) also showed that technology helps improve productivity by eliminating previously uncontrollable productivity factors. Thus, productivity has a tendency to improve in the long run.

Proverbs et al (1999) identified several factors that affect labor productivity. These include actual working hours, time allocated for breaks, number of weekly working days, level of supervision, skill levels and crew size.

2.5 WEATHER

Weather conditions at the construction site have a large impact on highway construction, and most construction operations are sensitive to weather conditions (Oglesby et al. 1989). Precipitation, extremes of temperature, and humidity cause productivity loss (Borcherding 1991; Halligan 1994) and may even cause activities to be delayed. Hot temperature may increase the frequency of workers' travel time as these workers may try to take shelter more frequently in order to avoid heat. As a result, productive time may be reduced (Borcherding 1991). Cold temperature may increase workers' idle time as the workers tend to stop their work warm themselves up around heat sources (Borcherding 1991). Weather also affects work operations such as foundation, retaining wall, and pipework, because many of these work operations have to be stopped to protect work quality (TxDOT 1993).

Several studies have been conducted to quantify the effects of adverse weather on labor productivity. Grimm and Wagner (1974) conducted a study to measure the effects of temperature and humidity on masonry productivity. It was reported that masonry productivity started to decrease beyond the temperature of 75 °F or above 60 percent relative humidity.

An experimental study (NECA 1974) conducted by the National Electrical Contractors Association found that productivity decreased when the temperature was above 80 °F or below 40 °F, or when relative humidity was above 80 percent. Another study carried out by Thomas et al. (1999) found that cold temperature caused a 32 percent drop in steel erection labor productivity. Labor productivity would be more seriously affected when their inabilities to carry out production operation properly were affected by rain that caused flooding and muddy working conditions. Such conditions made movement of both labors and equipments difficult and thus slowed down productivity. Thus, weather should often be considered as an important driver of productivity.

2.6 SCHEDULED OVERTIME

Overtime work often affects productivity. Scheduled overtime is often considered as “a planned decision by project management to accelerate the progress of the work by scheduling more than forty work hours per week for an extended period of time for much of the craft work force” (Thomas and Raynar 1999). Scheduled overtime causes fatigue and reduces motivation among workers and indirectly contributes to losses in labor productivity. Many studies have attempted to quantify the effects of such overtime on labor productivity. The 1980 Business Roundtable republished the findings of weekly productive returns from working fifty or sixty hours a week for various numbers of weeks. In the late 1960s, Weldon McGlaun reported these findings to members of the National Constructors Association. It was found that productivity during the first week of scheduled overtime fell dramatically and that productivity continued to go down every other week. After working for fifty hours per week continuously for seven weeks, the weekly output became similar to that when the workers actually worked forty hours per week. For a sixty work-hour week, by the ninth week of scheduled overtime, the weekly output was similar to that of working for only forty hours a week. Figure 2.3 clearly exhibits such phenomenon.

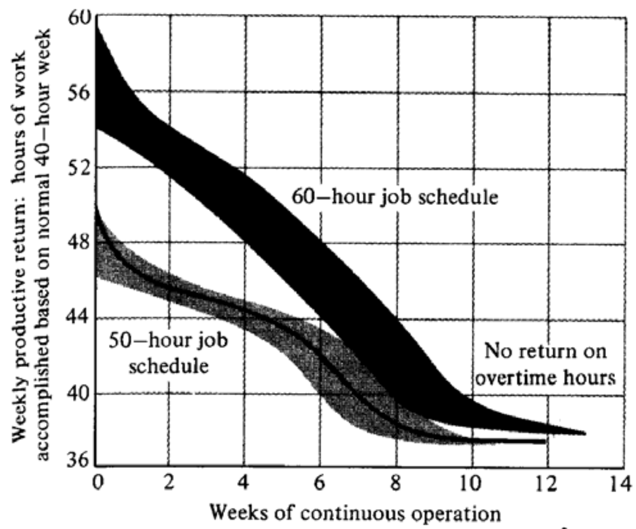


Figure 2.3: Effects on productivity from Overtime Work (BRT, 1980)

However, conclusions from a study conducted by the Construction Industry Institute (1988) were inconsistent with previous findings. This study concluded that "productivity does not necessarily decrease with an overtime schedule" based on monitoring twenty-five crews on seven projects (three insulation crews, seven pipe crews, eleven electrical crews, one formwork crew, one rebar crew, and two concrete crews).

Thomas and Raynar (1997) quantified the effects of scheduled overtime on productivity by studying the productivity of electrical and piping craftsmen on four active construction projects. Their study reported a loss of 10–15 percent efficiency for both scheduled overtime scenarios of fifty working hours and sixty working hours per week.

Noyce and Hanna (1998) highlighted that schedule compression leads to lower labor productivity but the impact on productivity could be reduced if proper planning is carried out.

Thus, productivity loss from overtime work depended on many factors. Though researches cannot agree on the effect but they generally concluded that it has negative impact on productivity.

Literature review also found that material shortage, inadequate planning, location congestion and accessibility, project uniqueness and safety regulations, have huge impacts on productivity (Kaming et al (1997), Allmons et al (2001) & Murawski (2001)).

2.7 DISRUPTIONS

Disruptions can have huge impact on construction productivity. Disruptions can be divided into two categories: short-term disruptions and long-term disruptions. A short-term disruption leads to productivity loss because extra work is needed to overcome the obstacles causing disruptions. A long-term disruption may even eradicate the productivity increases from learning curve effects (Halligan 1994).

Thomas and Raynar (1997) classified disruptions into 13 categories, these include resources, material, tool and equipment availability, rework, change order, management, congestion, out-of-sequence work, and supervisory failure. Thomas et al

(1999) found that disruptions caused a loss in production momentum and had a "ripple effect" on subsequent productivity. Furthermore, Thomas et al (2002) showed that high variability in work flow, high wastage and low flexibility in field capacities resulted in negative impact on productivity. Both Allouche (2001) and Thomas et al (1986) highlighted the importance of productivity stability in achieving high productivity.

In their study, each type of disruption was measured by the frequency of occurrence during a working week. It was found that more working days per week were required when there was a higher frequency of disruption. Disruptions can rarely be forecasted at the design stage and as a result, disruptions should only be accounted for during the construction stage and used to adjust the estimated rates.

Construction disruption has attracted concern from industry as it slows down production and delays completion time. Significant disruptions add up to the cost and time that are usually not reflected in the initial project cost. Disruptions can also cause disputes among the different parties that are involved in the construction process.

In general, disruptions can cause two types of delays. First, production may be stopped during the period of disruptions. Tracking the total number of reduced production periods are important. Second, productivity of resumed production after a disruption may be slower than the productivity prior to disruption. Such reduction after production resumes is usually not accounted for during project time estimation but can significantly reduce overall site productivity and lead to lower production rates.

There are many ways to measure delays and disruptions. Kartam's (1999) proposal for determining whether contractors can claim for time delay is to compare the differences between the original production rates and the affected rates. The method of calculation is by dividing the total work quantity by the total number of days to complete that quantity. By comparing the original production rate to the affected one, impacts due to delays can be effectively measured.

Shi, Cheung and Arditi's (2001) proposed method for computing delays involved determining the relationships and impacts between different work and then built know delays into the schedule. Assumed factors can then be used to generate the actual delay impact on the overall scheduled. This method relies heavily on experience to identify the assumptions and is used after delays have occurred.

Bubshait and Cunningham (1998) identified three common methods of schedule delay analyses: (1) As-planned methods; (2) As-built method; and (3) Modified As-built method. The methods discussed above are aimed at studying the impact of delays and the actual schedule. These methods require delays to be complete before they can be measured and thus cannot be used as a forecasting tool to estimate the impact of delay.

Allouche et al (2001) highlighted that uncontrollable soil conditions complicates construction process and affects productivity but better knowledge of the controllable factors could help constraint variability in productivity. Soil problems will still dominate construction research in the foreseeable future.

2.8 CONGESTION AND ACCESSIBILITY

Ovararin and Popescu (2001) conducted a study to quantify the effects of sixteen field factors on productivity loss in masonry construction. Fifty participants who were either owners or chief estimators of masonry contractors were randomly selected, and a survey package was distributed to them.

In their study, productivity losses caused by levels of congestion and accessibility were quantified. The definitions of levels of congestion and accessibility are shown in Table 2.1. The disruptions of an additional crew working in the same area were evaluated. The results reported that congestion caused 10–32 percent productivity loss. Levels of accessibility were evaluated by considering the convenience of accessing the work area and the distance between the work area and material storage. They found that disruptions associated with accessibility caused 13–35 percent productivity loss.

Table 2.1: Factor definitions (Ovararin and Popescu (2001)

Field Factors	**Standard field conditions**		
	Minor	**Moderate**	**High**
Congestion	An additional crew/contractor working in the same area 1 day/week	Additional crews/contractors working in the same area 2~3 days/week	Additional crews/contractors working in the same areas everyday
Accessibility	4 days/week, <25 yards to materials storage	2~3 days/week, 25~50 yards to material storage	Once/week, > 50 yards to materials storage

Sizes of materials caused variation in construction and installation duration (Leu and Hwang 2001). Large precast panels may have reduced overall installation time but they posed more logistical problems while smaller panels require more installation time but faced less problems with transportation disruptions. Thus, material sizes have different effects on productivity. In addition, Poh and Chen (1997) showed that design has huge impact on productivity.

2.9 REGION

The location of a construction project was found to be a factor influencing construction production rates. A productivity study conducted by Koehn (2001)found that production rates varied in different regions in Bangladesh. Lack of training and improper supervision was the major reason for low production found in rural areas. Most big construction companies in Bangladesh were located in urban areas, and only big construction companies provided training for the operation of sophisticated equipment which caused production deviation between rural and urban areas.

Low productivity can also be due to workers' fatigue from long-distance commuting (Borcherding and Alarcon 1991). The location of a project can affect both workers' motivation and the availability of advanced tools or equipment. Project location can also have an impact on the availability of skilled labor (AbouRizk et al. 2001). Worker motivation (Borcherding 1980; Borcherding and Garner 1981) and the availability of skilled labor (Koehn and Brown 1985) both have a huge impact on construction productivity.

Location conditions, work space and construction methods influence choice of equipment (Sawhney and Mund 2002) and correlations between equipment and these factors have to be examined.

2.10 THE EFFECTS OF LEARNING AND LEARNING CURVE

When performing repetitive tasks, productivity tends to increase as the number of cycles increase. This increased productivity is due to experience gained from previous tasks, improved resource allocation, better engineering support, better management and supervision, and development of more efficient methods (Thomas et al. 1986). Thomas et al. conducted a study to evaluate the efficiency of various learning curve models on productivity estimation and to investigate the learning rates from four field studies. The learning rate is the rate of change of the cumulative average man-hours when production doubles. It was found that the learning rate was never constant, and therefore its relationship with productivity is never linear. Instead, the relationships can better be expressed with the cubic, logarithmic or power model.

2.11 RAINFALL

Rainfall has a great impact on highway construction productivity. El-Rays (2001) presented a decision support system that could quantify the impact of rainfall on productive day losses and managed to estimate the duration for certain types of construction operations in highway construction projects. Data were acquired from interviews with experts involving in highway construction. The experts indicated that the types of construction operation, intensity of rainfall, and drying conditions on site were the three most significant factors that suffered the most productivity losses due to rain falls. In addition, El-Rayes and Moselhi (2001) indicated that earthmoving, construction of the base course, construction of drainage layers, and paving construction were the four tasks in highway construction that were most sensitive to rainfall.

2.12 ADVANCEMENT IN TECHNOLOGY

Technological advancements often lead to improvement of construction productivity. Such increase can be attributed to increased level of control, amplification of human energy, and information processing (Schexnayder and David 2002). Bhurisith and Touran (2002) conducted a case study with regard to obsolescence and equipment production rate and the ideal production rates of wheel-type loaders, track-type loaders, scrapers, and crawler dozers were collected from the 1983, 1992, and 1998 *Caterpillar Performance Handbooks*. The results showed that production rates under ideal conditions have increased and average of 1.58 percent annually due to technological advancements.

Jonason et al. (2002) studied the productivity of earthwork for different types of advanced positioning systems and found that those systems lead to time savings and cost reduction of earthwork construction. However, there are still several shortcomings that inhibit the usage of these advanced positioning systems. The applications of 2-D and 3-D guidance technologies are limited to work areas with direct line-of-sight between the control station and the receiver on the equipment and GPS-related signal noise can affect the accuracy of measurement.

Goodrum and Hass (2002) studied the change of productivity and technology according to productivity data published by RS Means, Richardson, and Dodge between 1976 and 1998. They found a substantial improvement in partial factor productivity among activities that have had significant improvements according to a technology index. The technology index was evaluated as a function of level of control, amplification of human energy, information processing, functional range, and ergonomics of equipment. It was found that site work has had the greatest improvement in mean partial factor productivity and technology index when compared with other work activities.

Allmon et al. (2000) examined changes in construction productivity and unit cost for twenty work items from the productivity data published by RS Means between 1974 and 1996. They found that the productivity of soil compaction and concrete placement increased by 260 percent and 55 percent, respectively and it was reported that new technology was the main driver of such improvement.

2.13 TRAFFIC AND CONGESTION

Jiang (2003) studied the effects of traffic flow on the construction productivity of hot mix asphalt pavement. He observed 24-hour traffic flow at a crossover work zone and used the queuing theory to compute the cycle time of transporting trucks in a hypothetical hot mix asphalt operation. Construction productivity of hot mix asphalt pavement was computed based on the cycle time and an assumed number of transporting trucks. It was found that traffic delays increased the cycle time of transporting trucks. As a result of increasing cycle time, the construction productivity, in terms of tonnage per hour, decreased. However, adding more transport trucks could balance the negative effects of congested traffic flow.

Guo (2002) study on site congestion showed that site congestion yielded lower productivity and found that factors that affect such congestion included space availability, layout space, route length, space usages and utilization.

2.14 METHODS OF PRODUCTIVITY ANALYSIS

Expert systems are another technique employed to deal with relationships between productivity and driving factors. Hendrickson et al. (1987) developed an expert system to predict the activity duration of masonry construction. There were two steps for the system to work. The first step was to estimate the maximum expected productivity, and the subsequent step was to adjust the maximum rate to a reasonable rate according to the characteristics of the job or site. The information associated with productivity was established from interviews with experienced masons and supporting laborers. Another expert system was developed by Christian and Hachey (1995) to estimate the production rate of concrete pouring. Using simple question-and-answer routine, this expert system was able to estimate production rates of concrete pouring based on established decision rules.

In addition, neural networks had been used by many researchers (Karshenas and Feng 1992; Lu et al. 2000; AbouRizk et al. 2001) to predict construction productivity. A neural network is a system that has a capability of learning from continual data inputs. The greatest advantage of using neural networks to predict construction productivity is that it can include interactive effects of multiple factors during productivity estimation if the network is trained with adequate and representative data sets. In reality, the size and quality of the training data set usually limits the effectiveness of the neural networks.

2.15 OTHER FACTORS AFFECTING PRODUCTION RATES

Herbsman and Ellis (1995) found seventeen factors affecting overall construction duration of a transportation facility project. These include weather and seasonal effects, location of a project, traffic impacts, relocation of construction utilities, type of project, letting time, special items, night and weekend work, dominant activities, environmental, material delivery time, conflicting construction operation, permits, waiting and delay time, budget and contract payment control, and legal aspects. These factors have been identified by other researchers as well.

2.16 CONCLUSION TO LITERATURE REVIEW

Although many studies have addressed construction productivity, few studies have been undertaken to study production rates for highway construction time estimation. The purpose of this study is to examine and determine the production rate in two work areas — namely, earthwork and pavement construction for highway projects. Such information will help TxDOT improve the accuracy of highway construction time estimation and should lead to better project time management.

There are too many factors that affect production rates that to consider the impact of all these factors would be a daunting task. It is impractical to collect a sufficient number of data points to make such analysis relevant.

The conclusion from the literature review is that the research needs to focus on the most important factors that drive production rates, and these factors must be predictable at the design stage. As a result, the factors were predetermined and the following section will discuss the selected factors.

2.17 FACTORS CHOSEN BY THE RESEARCH

The following tables summarized the factors that were adopted by this research after reviewing the above literatures. The factors were separated into project, work item and work zone levels.

Table 2.2: Proposed project level factors

Factors from Literature	**Proposed Factors**
Construction Type	Project Type
Location	Location
Traffic Conditions	Traffic Flow
	Traffic Count
Rain	Weather (Precipitation)
Other weather impact	Weather (Winter Length)
Learning Curves	% of Construction Completion
Project Size	Contract Amount
Project Complexity	Technical Complexity
Nature of Contract	Contractual Drivers
Soil/Site conditions	Soil Types
	Clay Content of Site
	Land Slope of Site
	Water Table Depth of Site
Technology	Scheduling Technique used
Management	Contract Administration System
	Contractor Management Skill
Workers' related productivity	Work Schedule (Days/week)
	Work Schedule (Hours/day)

Table 2.3: Proposed work item level factors

Factors from Literature	Proposed Factors
Crew Size	Workmen Size
	Equipment Size
	Crew Size
Weather and other disruptions	Weather
	Equipment breakdown
	Utility Conflict
	Construction Accident
	Incomplete Crew Size
Size of operations/learning curves	Work Zone/Item Quantity
Types of construction	Orientation
	Materials/Types
Soil and other disruptions	Soil Type
Site Conditions	Location conditions

Table 2.4: Proposed work zone level factors

Factors from Literature	Proposed Factors
Site conditions	Work Zone Accessibility
	Work Zone Construction Congestion
Weather/Soil and site conditions	Work Zone Site Drainage Effectiveness
Soil Conditions	Clay Content of Soil
	Land Slope
	Water Table Depth

The project level and work zone level factors are applicable to all work items. However, there are two sets of work item level factors, one set is applicable to all work items and the second set is designed to capture factors that are only relevant to specific work items. However, all the factors were subjected to modification during the data collection process to better suit the research objectives.

2.18 DATA COLLECTION TOOLS

Data collection tools were developed to facilitate the data collection process and to enhance the accuracy of data. These tools consist primarily of data forms that were used to track production rates and identified factors. A "Data Computation/Analysis Sheet" is also designed to ease the process of data analysis. The tools helped to guide the data collection process and ensured that essential data such as time, quantities and factors affecting production rates were appropriately verified and collected. These tools are documented in the Appendices. The data were further divided into Project Level, Work Item Level, and Work Zone Level.

Project level factors are factors that are generally considered to have an effect on productivity owing to the nature of the project. These factors (also identified as candidate drivers in this research) include: (1) project type, (2) location, (3) traffic flow, (4) traffic count, (5) weather (rain and winter length), (6) percentage of project completion, (7) contract amount, (8) technical complexity, (9) contract day, (10) accelerated construction provision, (11) liquidated damages, (12) soil types, (13) clay content of soil, (14) land slope, (15) depth of water table, (16) scheduling technique used, (17) work schedule (hours/day and days/week), (18) contract administration system, and (19) contractor's management system. The tracking of these factors was done on a form called the "Production Rate Tracking; Project Level". This form was used to identify characteristics of a project and possible work items for which data related to production rates may be collected. The inputs for this form were completed during meetings with site personnel.

Work Zone level factors include factors that are related to the conditions of the work zone. The form is titled "Production Rate Tracking; Work Zone and Work Item Levels" and it consists of four data sheets: "Production Rate Tracking: Work Zone Level," "Work Item Sheet," "Production Rate Tracking: Work Item Level," and "Tracking Calendar." The "Work Zone Level" sheet was used to describe the conditions of the work zone in which the work item was being performed. It includes descriptions of the work zone characteristics, such as accessibility, congestion, and drainage effectiveness. The “Work Item Sheet” form was used to specify the scope of each work item (what is “Included” and what is “Not-Included”). It provided a generic guide to ensure consistency during the data collection process. Work elements included in the scopes of the work items were those that most directly represented actual production of the work item. The “Work Item Sheet” form also contains work item specific information and a list of possible work item specific factors that may affect the production rate of each work item. To accommodate the variability in each scope of work, a thorough survey was completed for each work item.

The “Production Rate Tracking: Work Item Level” sheet was used to record certain factors that can be better described with sketches and detailed wordings. Such factors include dimensions, shapes, and sections of the work items. Work quantities were also recorded for each data point. Other relevant information for this sheet include (1) quantities of the work items that were completed (2) time expended to construct these work items (3) the contractors’ working and non-working days (4) the reasons for non-productivity (5) other information that could be candidate drivers affecting productivity and (6) design drawings and other information that TxDOT personnel indicated as helpful.

The “Tracking Calendar” sheet was used to classify each calendar day into normal, half-day, or non-working day, according to the total hours of work operations for the work item in a given day. Possible factors affecting the operation were also indicated using notations as provided for on the sheet.

2.19 Job Site Selection

The first cycle shown in the following figure displays tasks associated with the district kickoff meeting. District meetings were conducted every twelve to sixteen weeks after the completion of data collection in the previous district. Such meetings were arranged to ensure that the district construction engineer and engineers from the area offices fully understood the research and would facilitate project selection and data collection process. Information on ongoing projects were obtained from the "Construction Report — Highways and Construction Monthly Estimate Report" on the TxDOT website (http://www. dot. state. tx. us/business/projectreports. htm). Projects that were less than 80 percent complete and had contract duration greater than 120 working days were recorded for further screening at the district meeting. Projects with production rates that could possibly be outliers, such as those with serious delays caused by legal problems or change orders, were eliminated. Visits to each district lasted three to five months, depending on the relevance and number of the projects selected.

2.20 Site Visitations and Data Validation

Once projects were selected, weekly visits to these jobs sites were scheduled. Data were provided by TxDOT site personnel and further verified and standardized and checked against field reports and visual inspections. The data sheets, as described in the previous section, were used to collect these data.

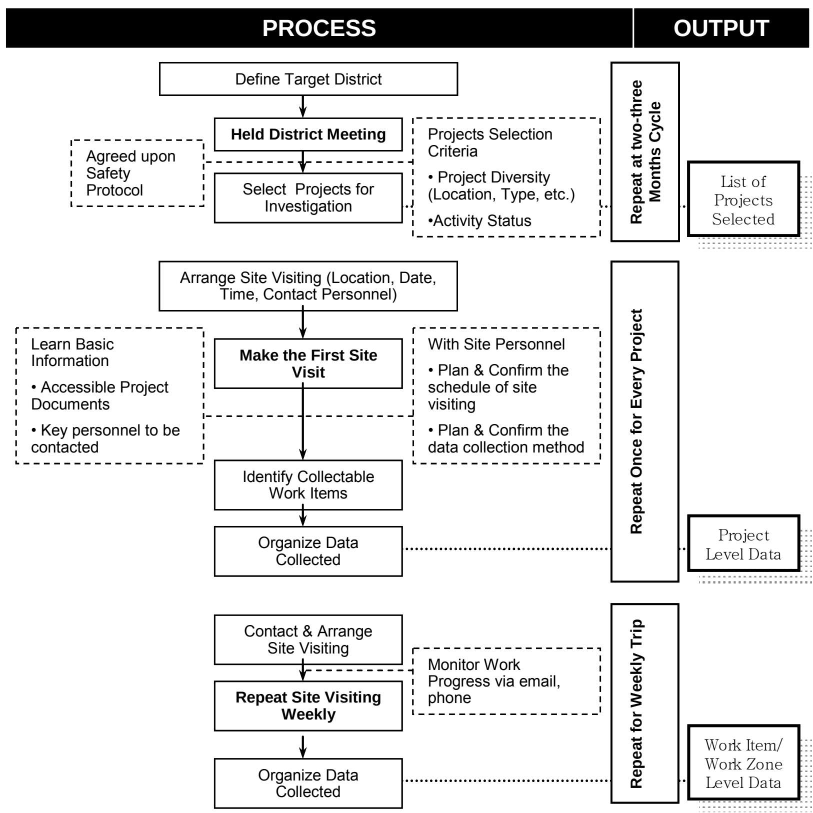
Benchmarking of a data point started at the first observation of a work item. Subsequent visits were conducted whenever necessary to complete the information for the form. The starting and ending nodes, as indicated in the data collection forms, were also used to guide the data collection process. The starting and ending nodes describe the scope of work operation that would be constituted in the measurement of production rates. Thus, data were only collected from work operations within the prescribed starting and ending nodes. These nodes can be found in the work item collection tools in the Appendices.

The observations for a data point ranged from a week to six weeks of work operations. Delays and variations of the work operations drove the length of observation periods.

Quantitative information, such as production quantities, working days, delay days, and non-working days, were collected from reliable information sources such as TxDOT's site personnel diaries and records to enhance accuracy. Qualitative information, such as work zone accessibility and congestion, were provided by the TxDOT site personnel and then visually verified by the researchers to ensure consistency. Foremen were also interviewed to better characterize progress of the previous two weeks in order to further enhance the quality of the data.

The data collection processes can be better visualized in the following figure. The data collection tools are documented in Appendix C, D, E, F and G. A safety protocol was also developed to ensure safety during every site visit. This protocol is documented in Appendix H.

Figure 2.4: Structure of Factors Analyzed



2.21 SUMMARY OF DATA COLLECTION PROCESS

A total of sixty-three projects constructed by thirty-four contractors and spreaded across seven TxDOT districts were selected. Projects were located across Texas and cost between $620,000 and $261 million. Projects were between 15 percent and 85 percent complete at the time of observation and had contract periods between 145 days to six years.

2.22 RATIONALE FOR PRODUCTION RATE COMPUTATION

Daily production quantities were collected from the selected sites. One data point constituted of a series of work operations for each work item. Depending on the work items, the production rates for each data point were calculated using the following formula as shown in the following table.

Table 2.5: Rationale for Production Rate Computation

<table>
<tr><th>Work Item</th><th>Definition for one data point</th></tr>
<tr><td>Drilled Shaft Foundations</td><td rowspan="2">One cluster of foundations where work operations can be carried out together in one operation without having to move equipment for more than 100 meters and/or detach equipment.</td></tr>
<tr><td>Piling Foundations</td></tr>
<tr><td>Reinforced Concrete Pipe</td><td rowspan="3">A line of pipes or culverts labeled under same identification number by TxDOT.</td></tr>
<tr><td>Pre-cast Concrete Box Culverts</td></tr>
<tr><td>Cast-in-place concrete box culverts</td></tr>
<tr><td>Inlets and manholes</td><td>One series of inlets and/or manholes lying on a line of pipes of culverts that were labeled under same identification number by TxDOT</td></tr>
<tr><td>Mechanically stabilized earthwall (MSE Wall)</td><td>A wall that is labeled under same identification number by TxDOT. Most MSE walls are between 3 feet to 80 feet tall and 100 feet to 0.25 mile wide.</td></tr>
<tr><td>Wingwall and headwall</td><td>One or two walls that are being constructed together in one operation.</td></tr>
</table>

The production rates were calculated for each data point by dividing the total quantities completed in the tracking period by the total number of days used to complete the operations. Each data point represents one production rate for each work item. For example, if 1,000 linear feet of pipe requires four days to construct, the production rate is 1,000 linear feet divided by four days, which is 250 linear feet per day (250 lf/day).

2.23 CORRECTION FOR DELAYS AND CREW SIZE

Delays are an inevitable part of any construction process, and thus simply calculating the total number of days and then dividing by the quantity yields unrealistic production rates that are not useful for TxDOT engineers. In order to eliminate such inconsistencies, the so-called the "half-day rule" was introduced. Crew work days were assessed as one whole work day if the delay effect caused by any of the factors amounted to less than two hours. When the delay was less than or equal to five hours but greater than two, the day would be counted as a half workday. Otherwise, it would not be counted as a workday. A work day having more than two hours of overtime was adjusted on the basis of actual overtime hours.

Table 2.6: Crew Work Day Computation - Half-Day Rule

Factors	**No Adjustment** ***(Effect Embedded in the Production Rate)***	**Corrected** ***(Effect isolated or adjusted)***
Weather (Rain, Too Wet, Snow, Wind etc) Unworkable Soil Condition Traffic Accident Construction Accident Equipment Down Time Material Unavailable Trade Problem Absenteeism	✓ **(IF Delay effect < ½ Day)**	✓ **(IF Delay effect ≥ ½ Day)**
Holidays, Non-Working Day, Non-Working Weekend, Day off		✓
Regional shortage(ROW, Unforeseen Condition, TxDOT Direction) Over-Time(>2 hours)		✓

Production rates were also adjusted according to crew size. Production rates that were gathered from larger crews were adjusted downward to fit the production rate of about one typical crew. Thus, production rates shown later reflect a standardized unit of crew day. In addition, weather impact on observed production rates has been removed. The treatment of weather for CTDS production rates is uncertain, as the issue is not documented.

2.24 ALTERNATIVE DATA SOURCES FOR DELAY MODELING

The second types of data collected for this research would be used to model the effects of disruptions on the predicted production rates. Production rates estimated during the design stage may not truly reflect the conditions where production may be affected by disruptions. As a result, production rates that are affected by disruptions would usually be much lower. However, it is rather difficult to foresee disruptions at the design stage and thus production rates can only be adjusted after disruptions took place.

The first set of data was collected in conjunction with this research while the second set of data came from highway projects conducted by a research project from the University of Houston. These data were collected from foremen's diaries and production rates were tracked on daily. These data include three types of information: Causes of disruptions, total number of days where disruptions took effect and the production rates during those days when production was disrupted. These data would be used to model disruptions on the work items.

2.25 STATISTICAL METHODS OF DATA ANALYSIS

The following sections discuss statistical techniques that were applied to analyze the data.

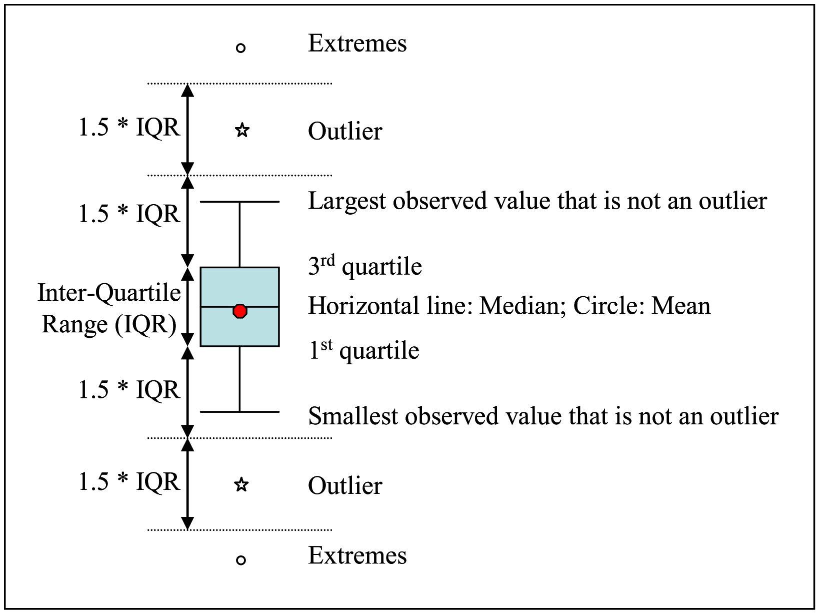
2.25.1 Descriptive Statistics and Box Plots

Descriptive statistics were often employed to summarize data such as mean, sum, count, and frequency of variables. In this research, data are shown on scatter-plots to demonstrate relationships or associations between two variables. The randomness of the scatters in the plots define the relationships of the data where decreasing randomness suggested increasing relationships.

.

A box plot is a statistical summary that presents mean, median, quartile, outliers, and extreme values in a graphical format. The following figure exhibits an annotated sketch of a box plot. The horizontal line in the shaded box represents the median or fiftieth percentile of the plotted sample. The dark circle highlights the mean of the targeted sample. The top and bottom ends of the box represent the third and first quartiles of the sample, respectively. The length of the box, from first quartile to third quartile, denotes the interquartile range (IQR). The horizontal line between third quartile and third quartile + 1.5 * IQR and between the first quartile and first quartile – 1.5 * IQR are the highest and lowest observed values, respectively, excluding outliers in the sample. Points beyond (third quartile + 1.5 * IQR) and under the (third quartile + 3 * IQR) as well as points under (first quartile – 1.5 * IQR) and beyond (first quartile – 3 * IQR) are outliers. Points beyond the limits of the outliers are considered extreme values.

Figure 2.5: Annotated Sketch of the Box Plot



2.25.2 Test of the Mean Difference

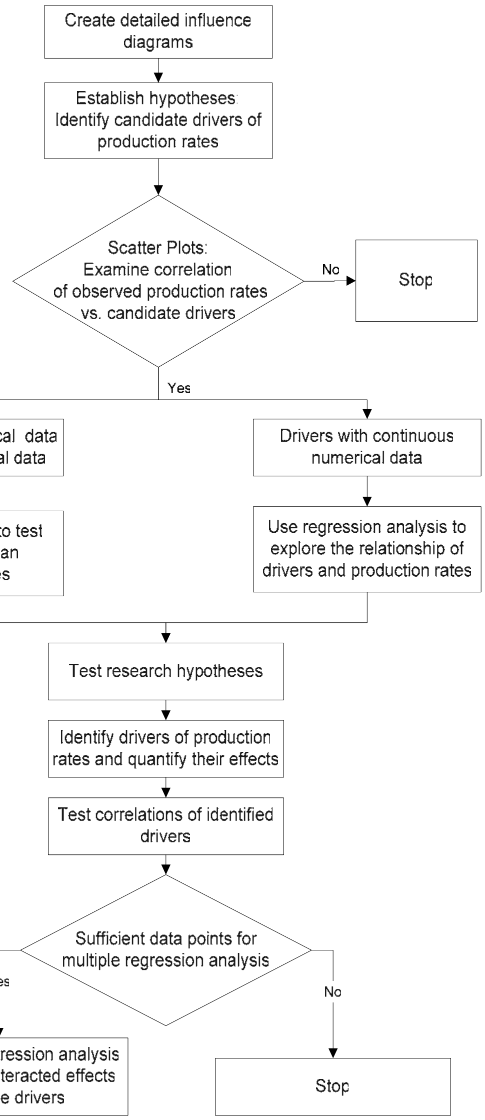
Because few original data are available to determine the distribution of the production rate data in the CTDS study, the average CTDS production rates were compared with the mean observed production rate for the seven targeted work items. The one-sample *t* test was used for this comparison.

2.25.3 Driver Analysis

Procedures used for driver analysis are shown in the following figure. Factors that were suspected to have significant effects on production rates and could be predicted at the design stage were considered as candidate drivers. Once these candidate drivers were identified, associated data were collected during regular job visits. Scatterplots were used to examine the relationship(s) between observed production rates and each candidate driver. Drivers without obvious relationship were excluded from further analysis. Two types of analysis approaches were adopted for further driver analysis. For those candidate drivers with continuous numerical data, regression analyses would be used to identify drivers of production rates and to quantify their effects. For those candidate drivers with discrete numerical or categorical data, the analysis of variance (ANOVA) or *t* test would be used to test the difference in mean production rate for the subsets in each candidate driver.

The quantitative effects of drivers on production rates would also be investigated. In addition, multiple correlations between the identified drivers of each targeted item would be computed to be used for reference when estimating effects of multiple drivers. If data were sufficient, multiple regression analysis would be used to further investigate the interaction effects of multiple drivers.

Figure 2.6: Flow Chart of Driver Analysis



The independent-samples *t* test is often used to test the differences between two population means. Three basic assumptions should be examined before applying the *t* test. The three assumptions are as follows.

(1) The two samples are independent.

(2) Populations are normally distributed.

(3) There are equal standard deviations between the two populations.

If the two samples are not independent, other test methods such as the paired-sample *t* test may be used. The second assumption stated that the populations are normally distributed. This assumption can be examined using the Q–Q plots, where all data should ideally fall on a line with 45° of slope if a typical normal distribution is valid. If this assumption is violated, the results of the *t* test can be used only when the size of samples is reasonably large. The last assumption stated that the standard deviations of the two tested populations should be equal. This assumption can be examined using the results of Levene's test in SPSS® v. 11.0 for Windows. The results of the *t* test may be incorrect if this assumption is violated, but the *t* test can have an accurate result if the sample sizes are equal under this circumstance.

2.25.4 Regression Analysis

Once a linear or nonlinear relationship between two variables is observed from the scatterplot, a linear or nonlinear regression analysis should be performed to verify whether a statistical relationship exists. The form of estimating a regression model is $Y_i = b_0 + b_1 * X_{1i} + b_2 * X_{2i}$. Y_i is the dependent variable that a study is trying to predict. X_{1i} and X_{2i} are the independent variables. The sample size should be checked to verify whether data are sufficient before regression analysis can be conducted. The sample size can be determined using the rules suggested by Green (1991). Green (1991) stated that the required sample size for a regression analysis can be determined by four values, namely, α (the probability of making a Type I error), $1 - \beta$ (one minus the probability of making a Type II error), R^2, and number of predictors.

Table 2.7: Sample Sizes & No. of Predictor (Green, 1991)

Number of Predictors	Sample Sizes based on Power Analysis		
	R^2=0.02	R^2=0.13	R^2=0.26
1	390	53	24
2	481	66	30
3	547	76	35
4	599	84	39
5	645	91	42
6	686	97	46
7	726	102	48
8	757	108	51
9	788	113	54
10	844	117	56
15	952	138	67
20	1066	156	77
30	1247	187	94
40	1407	213	110

The above table displays the required sample sizes to test the hypothesis that the population multiple correlation equals zero with a power of 0.8 and α of 0.05 based on power analysis. A regression model needs twenty-four data points for one predictor and thirty data points for two predictors when the α, $1 - \beta$, and R^2 values used to determine the statistical significance of a regression model are 0.05, 0.8, and 0.26, respectively. If the required R^2 used to determine the significance of a regression model increases, the number of data points may be reduced. Therefore, a total of 24 data points are required to perform simple regression analysis, and 30 data points are needed to perform a multiple regression analysis with two predictors in this research. However, less than twenty data points may be also employed for regression analysis if a higher R^2 is achievable.

In addition, the logarithmic model and the power model were employed to identify nonlinear relationships between selected significant drivers. SPSS® v. 11.0 for Windows was used to perform the linear and nonlinear regression analyses. Equation 2.1 exhibits a typical logarithmic model and equation 2.2 exhibits a typical power model.

Logarithmic Model: $\mathrm{Y_i} = \mathrm{b_0} + \mathrm{b_1} * \mathrm{Log}\ \ \mathrm{X_i} + e_i$ (2.1)

Power Model: $\mathrm{Log}\ \ \mathrm{Y_i} = \mathrm{Log}\ \ \mathrm{b_0} + \mathrm{b_1} * \mathrm{Log}\ \ \mathrm{X_i} + e_i$ (2.2)

There are six steps to be taken in order to perform a regression analysis. First, the dependent and independent variables should be checked to see whether they are approximately normally distributed. Violation of this assumption would lead to biased estimations. Second, a scatter-plot is developed to check for a plausible linear model, and then a box plot is used to detect outliers. Outliers should be removed before performing a regression analysis because they impact the trend and accuracies of the regression model. The third step is to fit the linear regression model to produce regression line fit. In this step, the R^2, adjusted R^2, and p values are computed and these values should determine the validity of the model.

The coefficient of determination, or R^2, is also called the measurement of the goodness of fit of the regression line. The value of R^2 always falls between 0 and 1, and indicates the proportion of variation of dependent variables that can be explained by the prediction model. The formula (Albright et al. 1999, p. 583) for calculating R^2 in a simple linear model is shown in Equation 2.3.

$$\mathbf{R^2} = 1 - \frac{\sum e_i^{\ 2}}{\sum (Y_i - \overline{Y})^2} \tag{2.3}$$

where $e_i = Y_i - \hat{Y}_i$ and $\hat{Y}_i = b_0 + b_1 X_i$

Y_i : observed value; $\hat{Y}_i$: fitted value of Y_i

where $\overline{Y}$ is the mean value of *Y*.

The fifth step is to inspect the results of testing coefficients of the fitted model. The *t* test is applied to test the coefficients. The *p* values of the *t* tests should be used to check whether the coefficients of the fitted model are statistically different from 0. A *p* value less than 0.05 indicates that the null hypothesis of a coefficient being equivalent to zero at 5% level of significance. In contrast, a *p* value not less than 0.05 represents that the tested coefficient is not statistically different from zero and, thus, there is no relationship between the dependent variable and the independent variable. The last step is to check for violations of the model assumptions. These include the (1) constant variance of errors, (2) normal distribution of errors, and (3) level of correlations between explanatory variables.

The constant variance of errors can be examined by plotting the scatter-plot of the predicted value of the fitted model versus the residuals. Non-constant variance of errors found in the regression model usually indicates the need for transforming the variables or adding an alternate variable in the fitted model. The normal distributions of the variables and errors can be inspected by observing their Q–Q plots. If the data are perfectly normally distributed, the points in the Q–Q plot will cluster around the 45° line while large deviations from a 45° line signal non-normality of a certain type (Albright et al. 1999, p. 486).

2.25.6 Correlation Analysis

The Pearson product–moment correlation tests were used to check the correlations between the explanatory variables. The Pearson product–moment correlation, or γ, is a value between -1 and 1. A correlation equal to or near zero indicates no linear relationship existed between the two variables. On the other hand, a correlation with a magnitude close to 1 indicates a strong linear relationship. Rejection or acceptance of the variable depended on the research requirements.

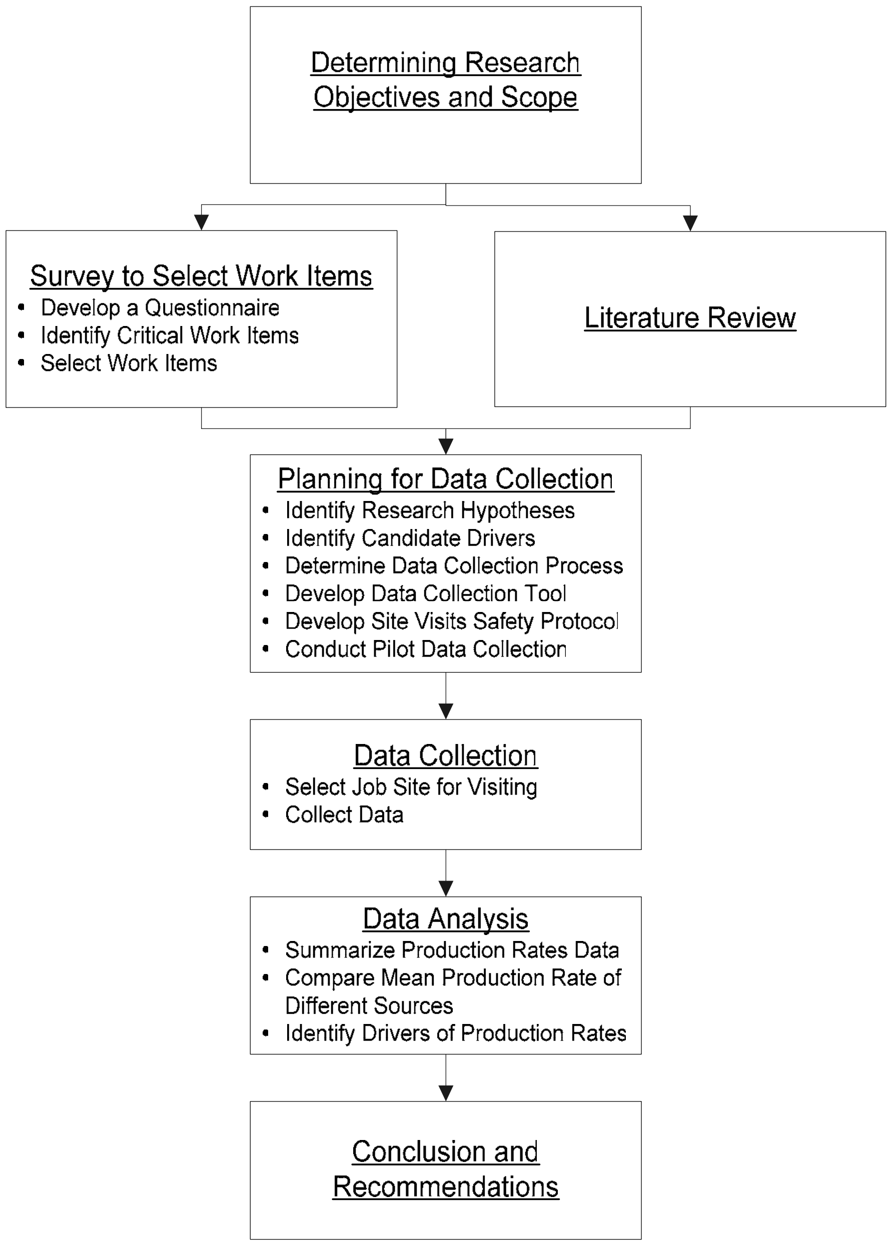
2.26 SURVEY ON CTDS USAGE AND IMPORTANCE

A survey was carried out to examine the usage level of CTDS in different TxDOT districts. The detail results of the survey are documented in Appendix K.

2.27 CONCLUSION

The complete set of the finalized data collection tools are shown in the Appendices. Figure 2.7 summarizes the entire data collection, analysis, and conclusion process employed in this research.

Figure 2.7: Research Methodology



CHAPTER 3: DATA ANALYSIS: DESCRIPTIVE STATISTICS AND COMPARISON WITH CONTRACT TIME DETERMINATION SYSTEM

3.1 SITE OBSERVATION DATA

Sixty-three projects in nine Texas Department of Transportation (TxDOT) districts were selected for the study. Weekly visits were scheduled for these projects over the time period indicated in Table 3.1. Ad hoc visits to some of these projects were also scheduled to collect more data on work items that had not reached the required number of data points. Table 3.1 summarizes the details of the scheduled visits, projects selected from each district, and the total number of data points.

Table 3.1: Schedule of Site Visits

Districts Visited	Dates of Scheduled Visits	Period of Ad Hoc Visits	Time Period of Visit (months)	Total Number of Projects	Number of Different Work Items	Total Number of Data Points
San Antonio	3/1/02 – 7/31/02	4/5/04 – 7/20/04	4	4	3	29
Yoakum	7/1/02 – 9/1/02	—	3	1	2	4
Austin	9/1/02 – 2/10/03	8/7/03 – 4/4/04	5	6	7	47
Dallas	11/7/02 – 2/25/03	5/5/04 – 7/12/04	5	4	5	40
Houston	3/20/03 – 10/16/03	1/5/04 – 5/5/04	7	9	9	83
Lubbock	9/16/03 – 11/06/03	—	2.5	3	5	8
Waco	11/13/03 – 02/07/04	—	4	6	6	54
Corpus Christi	4/13/03 – 10/1/03	4/4/04 – 6/20/04	5	6	8	54
Bryan	2/28/04 – 5/20/04	—	3.5	3	2	7
Total			-	42	-	326

There were a minimum of two to a maximum of sixteen projects selected from each district. The total number of projects that were selected from each district varied due to two main reasons. First, there were different numbers of projects under construction during the period of scheduled visits. For example, there were more than 200 highway projects underway in Houston during the period of scheduled visits, whereas there were only forty highway projects underway in Lubbock. Second, projects were selected only if the relevant work items were found in these projects. Fewer projects in a district indicated that there was less opportunities for investigating the nine targeted work items. Projects were not selected if none of the nine work items were under construction during the period of scheduled visits.

The research team also carefully selected projects in each district so that there were sufficient data points to represent production rates in rural, urban, and metropolitan regions.

The following table documents the total number of data points for the nine work items, the total quantity of data points, the units adopted by the research, the total working days for all data points, and the total number of districts and projects from which the data were collected.

Table 3.2: Consolidated Data Points

Item Number	Work item	Total No. of Data Points	Total Quantity	Units	Total No. of Work Days	Total No. of Districts	Total No. of Projects
409	Prestressed concrete piling	22	1,388	Piles	73.5	2	8
416	Drilled shaft foundation	38	19,733	lf	167	8	17
423	MSE wall	50	107,604	sf	242	6	13
423-1	MSE wall — copings	11	7,084	lf	30	3	6
423-2	MSE wall — footings/leveling pads	11	13,163	lf	43.5	3	7
462-1	Precast concrete box culverts	49	34,226	lf	215	7	17
462-2	Cast in place concrete box culverts	12	3,310	lf	272	4	7
464-1	RCP 18–42 in.	50	30,013	lf	231	8	22
464-2	RCP 48–72 in.	21	11,187	lf	140	5	10
465	Inlets and manholes	37	278	Inlets/ manholes	129	7	21
466	Wing wall/head wall	28	6,397	sf	194	5	10

Total Number of Data Points for each of the work items ranged from a minimum of eight to a maximum of 50. Total Quantity indicates the total quantity of work that was observed in this research. Total Number of Work Days indicates the total number of work days that were tracked by the researcher for each work item. The Total Number of Districts and the Total Number of Projects indicates the total number of districts and projects, respectively, from which the work items were observed during the scheduled visits.

3.2 AS-BUILT DATA

Production rates calculated from historical records were also analyzed. These historical records came from four selected projects. The contractors from these projects were found to have kept very reliable records of the quantities of work and the time spent to complete those quantities. These contractors were also very willing to share these data with the research team. The production rates were calculated by dividing the quantities of work by the total working days for completing these work quantities where days affected by disruptions were not included. These projects were labeled as As-Built 1, As-Built 2 and As-Built 3. Because historical records from field operations rarely included records on production rate driver parameters, the production rates from these historical records were not used to analyze production rate drivers and to model the relationships between drivers and production rates. Detailed descriptions of the as-built data are below.

3.2.1 As-Built 1 and As-Built 2

Data came from contractors' historical records between March 2002 and August 2002. The projects were 55–80 percent complete during that time period. Relevant documents, such as construction plans and workers' time cards, were also investigated to ensure consistency with the historical records.

3.2.2 As-Built 3

Source of these data came from contractor's historical records between August 2001 and November 2002. The projects were 30–50 percent complete during that time period. Relevant documents, such as construction plans and workers' time cards, were also investigated to ensure consistency with the historical records.

3.3 DIFFERENCES BETWEEN CTDS AND OBSERVATIONS

Various differences between Contract Time Determination System (CTDS) production rates and those derived from field observations are analyzed in this section. Three comparisons were made between CTDS and observed data. First, an analysis was conducted to compare the differences between the units adopted by CTDS and those adopted by this research. Second, the differences between the work scope for the selected work items adopted by CTDS and the work scope adopted by this research were analyzed. Third, the differences between CTDS production rates, the observed production rates from this research, and the production rates calculated from the historical records were compared. The key differences are summarized at the end of this chapter. In addition, weather impact on observed production rates has been removed. The treatment of weather for CTDS production rates is uncertain, as the issue is not documented.

3.3.1 Units Applied and Definitions

Analysis of the adopted units of CTDS and this research highlighted two main differences. First, this research and CTDS adopted *crew day* and *day* for their time units, respectively. Crew day was adopted in this research to indicate that increasing crew size can increase production rate. The CTDS time unit of day does not clearly indicate the applicability of production rate to crew sizes. Thus, production rates shown and analyzed in the following chapters of this research are for a single crew size.

In interpreting research data, designers should assume that only one standard crew is used to execute the construction. Adjustments can work for those cases when it is know that the contractors will use more than a single crew in order to speed up construction.

Second, there are additional differences in the units adopted for prestressed concrete pilings and concrete box culverts. The Project Monitoring Committee for this research adopted different units for two main reasons. First, the new units enhance the efficiency of the time estimation process. Second, these units can be more easily integrated into TxDOT project schedules. The following table summarizes the units adopted by CTDS and this research.

Table 3.3: Units Adopted - CTDS versus Research

WI#	**Major Work Items**	**Production Rate Unit Adopted by CTDS**	**Production Rate Unit Adopted by Research**
409	Prestressed concrete piling	lf/day	ea/crew day
416	Drilled shaft foundations	lf/day	lf/crew day
423	Retaining wall — specifically MSE wall	sf/day	sf/crew day
462	Concrete box culverts and storm drains (both cast in place and precast)	cy/day	lf/crew day
464	Reinforced concrete pipe	lf/day	lf/crew day
465	Manholes and inlets	ea./day	ea/crew day
466	Head walls and wing walls	sf/day	sf/crew day

3.3.2 Scope Differences

Table 3.4: Scope Differences - CTDS vs Research

WI#	Major Work Items	Scope Included in CTDS	Scope Determined as Useful by Research	Differences
409	Prestressed concrete piling	Includes installation of piling for bridge foundation but it is silent about whether the rate includes equipment setup time for piling	The rate is similar to that defined by CTDS because it is applicable to bridge foundation only. The rate also includes equipment setup time	The only unclear area is whether the rate in CTDS includes equipment setup
416	Drilled shaft foundations	No mention in CTDS	From equipment setup, drilling, casing, handling and placing of reinforcement, handling and placing of concrete and tub removal	Not sure
423	Retaining wall — specifically MSE wall	The layout, forming, reinforcing, placing, curing and removing forms for cast in place reinforced concrete retaining walls	The grading and compacting of foundation to removal of placing tie strips on only precast MSE walls	The main difference is that CTDS rates are for cast in place walls whereas the research looks only at MSE walls
462	Concrete box culverts and storm drains (both cast in place and precast)	The excavation, installation, and backfilling of cast in place concrete box culverts on the construction site (If precast units are used, the units should be changed to lf and appropriate production rates should be substituted)	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using precast or cast in place culverts	Cast in place in CTDS
464	Reinforced concrete pipe	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using manufactured pipe	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using manufactured pipe	None
465	Manholes and inlets	The installation of premanufactured inlets and manholes for drainage and sewer systems on the construction	The research covers the installation of all cast in place and precast inlets and manholes and applicable only to sewerage pipe extension	Inclusion of cast in place inlets and manholes for this research and rates for the research includes only pipe extension
466	Head walls and wing walls	No mention in CTDS	Excavation, base preparation, forms and reinforcement installation, handling and placing of concrete and apron, curing, removal of forms and backfills	Not sure

Scope of work item describes the extent and content of the construction processes that are included in production rate measurement of work items. Excluding or including any part of a process could result in significant differences in measured production rates.

There are several differences between the scope of work items adopted by CTDS and that adopted by this research. The table above summarizes these differences. However, for comparison purposes, no adjustments were made to the affected CTDS production rates because the difficulty in carrying out such adjustment.

3.3.3 CTDS versus Observed Rates

The production rates in the CTDS were represented in three values: low, mean, and high. These values were calculated from survey inputs, but the calculation technique was not documented in the report.

Similarly, three such values were also computed from the observed production rates. The low and high values were the lowest and highest observed production rates, and the mean value was calculated by summing all the observed production rates and dividing the summed rates by the total number of data points. The following tables summarize these production rates.

Significant differences are observed by comparing the rates in the table. For example, the CTDS low, mean, and high production rates for Inlets and Manholes are 1, 2, and 3 respectively, but research observations found that the low, mean, and high production rates were 0.20, 1.84, and 3.00 ea/crew day, respectively. This example highlights that there are significant differences between the production rates. It also highlights that CTDS fails to capture certain important variables, like accounting for cast-in-place inlets and manholes.

Table 3.5: Adopted units – CTDS vs Research

Item #	**Work item**	**Sources**	**Units Adopted**	**Observed Production Rates**		
				Min/Low	**Mean**	**Max/High**
409	Prestressed concrete piling	Observations	ea./crew day	1.75	6.40	10.67
		Observations	lf/crew day	140	968	3348
		CTDS	lf/day	200	300	400
416	Drilled shaft foundation	Observations	lf/crew day	40.00	111.60	278.75
		CTDS	lf/day	200	300	400
423	MSE wall	As-built	sf/crew day	212	550	850
		Observations	sf/crew day	225.00	453.50	1,164.25
		CTDS	sf/day	100	150	200
423-1	MSE wall — copings	Observations	lf/crew day	150.50	284.10	352.94
		CTDS	N.A.			
423-2	MSE wall — footings/leveling pads	Observations	lf/crew day	67.73	178.09	300.00
		CTDS	N.A.			
462-1	Precast concrete box culverts	Observations	lf/crew day	14.40	141.98	322.40
		CTDS	N.A.			
462-2	Cast in place concrete box culverts	Observations	lf/crew day	1.83	10.36	16.28
		Observations	cy/day	8.64	25.1	57.8
		CTDS	cy/day	10	15	20
464-1	RCP 18–42 in.	As-built	lf/crew day	66	150	240
		Observations	lf/crew day	36.00	138.67	189.37
		CTDS	lf/day	100	200	300
464-2	RCP 48–72 in.	Observations	lf/crew day	9.00	94.92	193.80
		CTDS	lf/day	100	200	300
465	Inlets and manholes	Observations	ea./crew day	0.20	1.84	3.00
		CTDS	ea./day	1	2	3
466	Wing wall/head wall	Observations	sf/crew day	13.50	35.37	92.31
		CTDS	sf/day	100	150	200

The units adopted for Cast-in-place Concrete Box Culverts and Precast Concrete Piling Foundations are also different. The new units are adopted as TxDOT designers highlighted that these new units ease the process of time estimation at the design stage. Most designers cannot easily estimate the total length of piles that they intend to design since piling depths depended on the soil conditions and stratum. In addition, extra effort has to be carried out to calculate the volume of Concrete Box Culverts and it does not improve the accuracy of estimation. Thus, the new unit should significantly improve the speed of the estimation process without compromising the quality of the estimates.

In addition, the CTDS production rates for Concrete Box Culverts are applicable only to the cast-in-place (CIP) type and not applicable to the precast type. This research thus establishes new production rates for Precast Box Culverts as these types are more frequently used by TxDOT and have higher production rates than CIP culverts.

Other new additions include production rates for MSE Wall Copings and Level Pads. The purpose of including two separate items for MSE Wall construction is that separating the estimation process of MSE wall panels from copings and leveling pads would improve the accuracy of the estimates. In addition, as the speed of construction was found to be driven by the height of the wall, walls that were less than two panels tall had a significant portion of the production process dealing with installing copings and leveling pads. Thus production rates for such walls may be inaccurately estimated since production rates of each component of the MSE Wall are significantly different.

3.3.4 Box-Whisker Plots of CTDS, Observed, and As-Built Rates

Box-whisker plots were employed to allow for better visualization of the differences between the CTDS, the observed, and the as-built production rates. These plots are shown in the following figures. The plots were prepared for work items only if similar units were found in the CTDS and observations. As-built information for some of the work items was also not available, and thus the as-built rates of these items were not plotted.

Figure 3.1: Box plots — Drilled Shaft Foundation (lf/Crew Day)

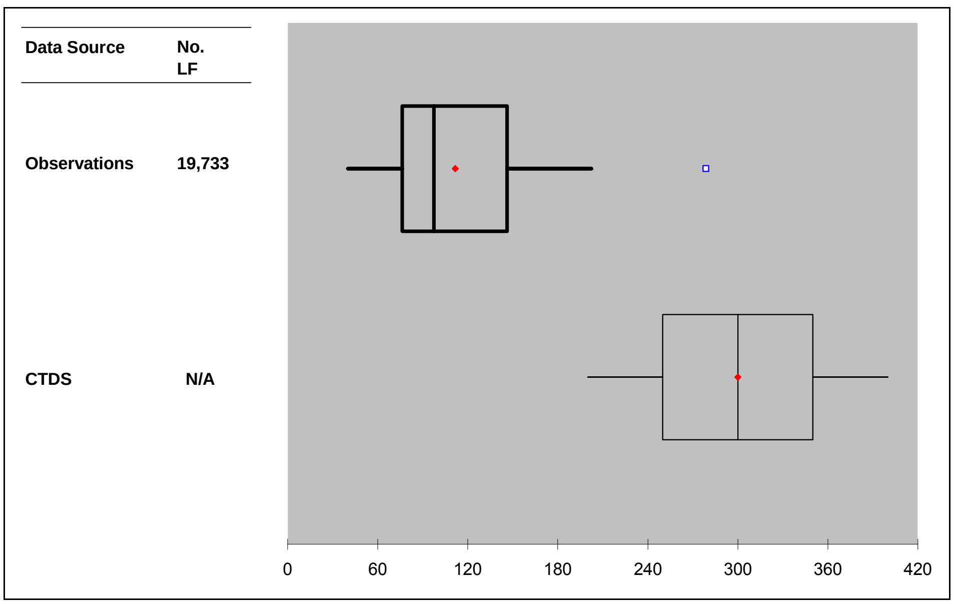


Figure 3.2: Box plots — Piling Foundation (lf/Crew Day)

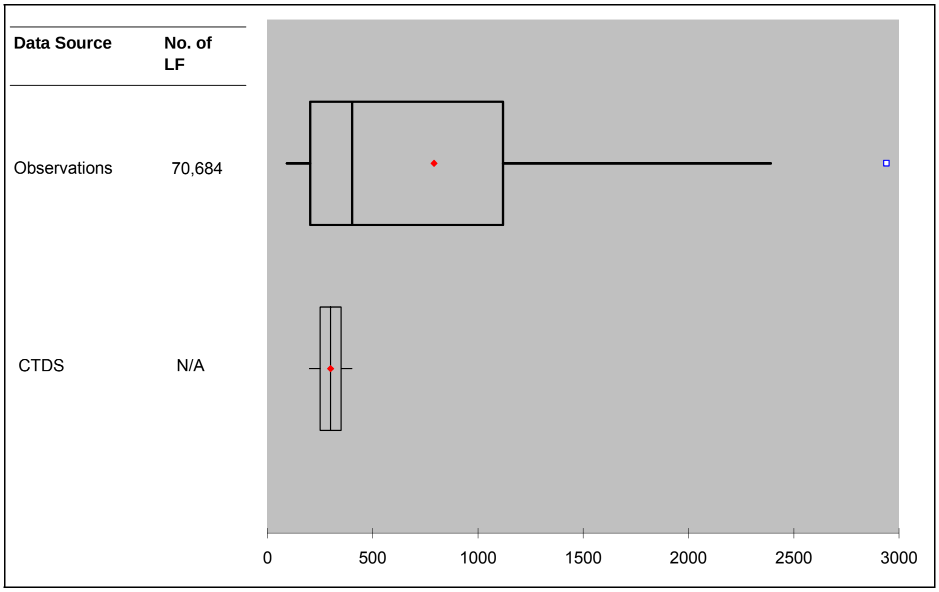


Figure 3.3: Box plots — MSE Wall (sf/Crew Day)

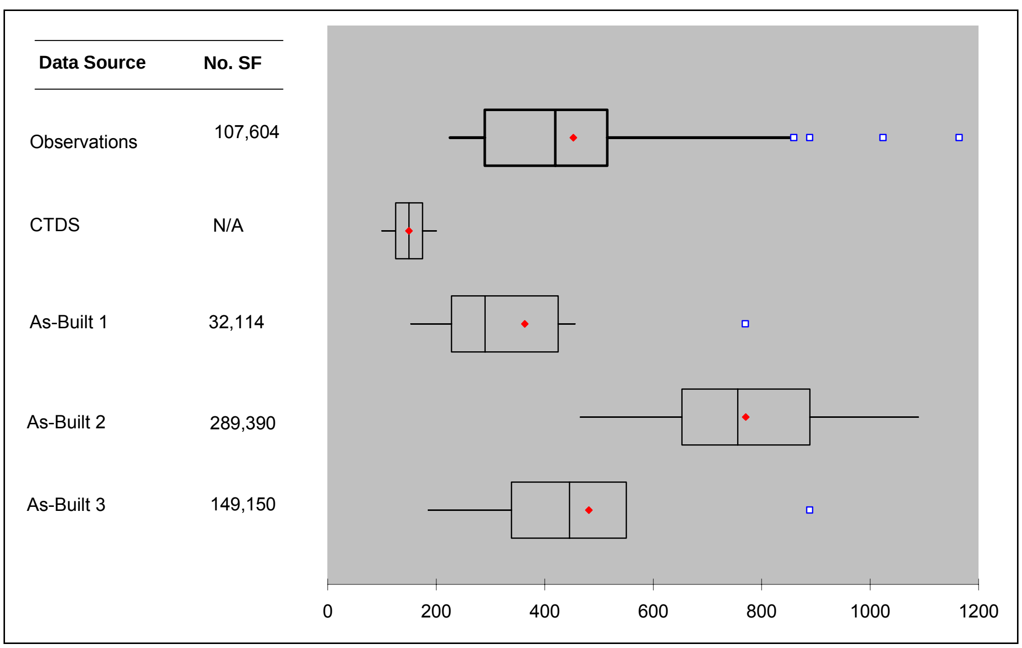


Figure 3.4: Box plots — RCP (lf/Crew Day)

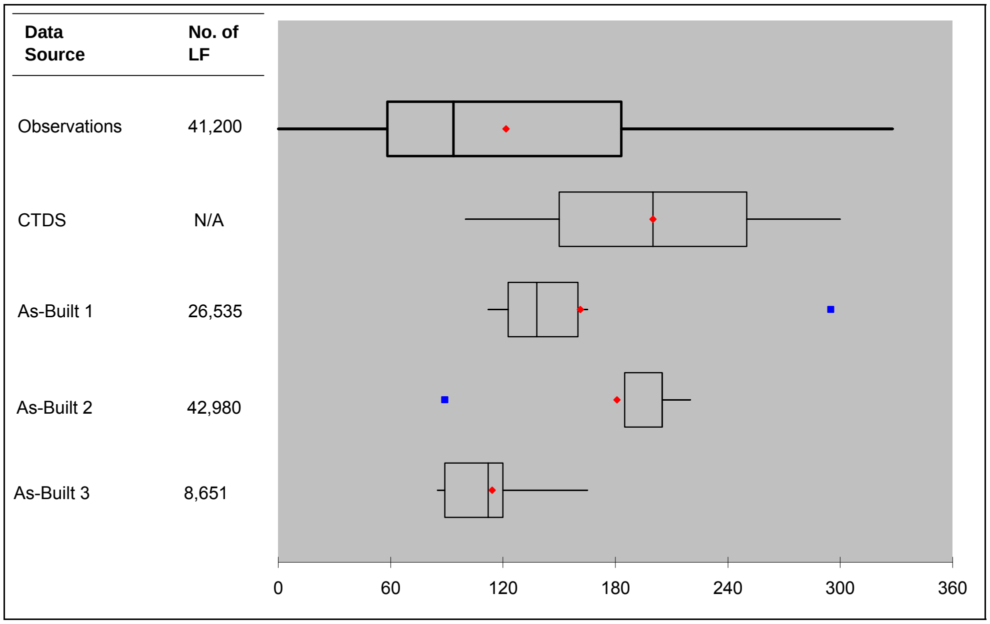


Figure 3.5: Box plots — PC Concrete Box Culverts (cy/Crew Day)

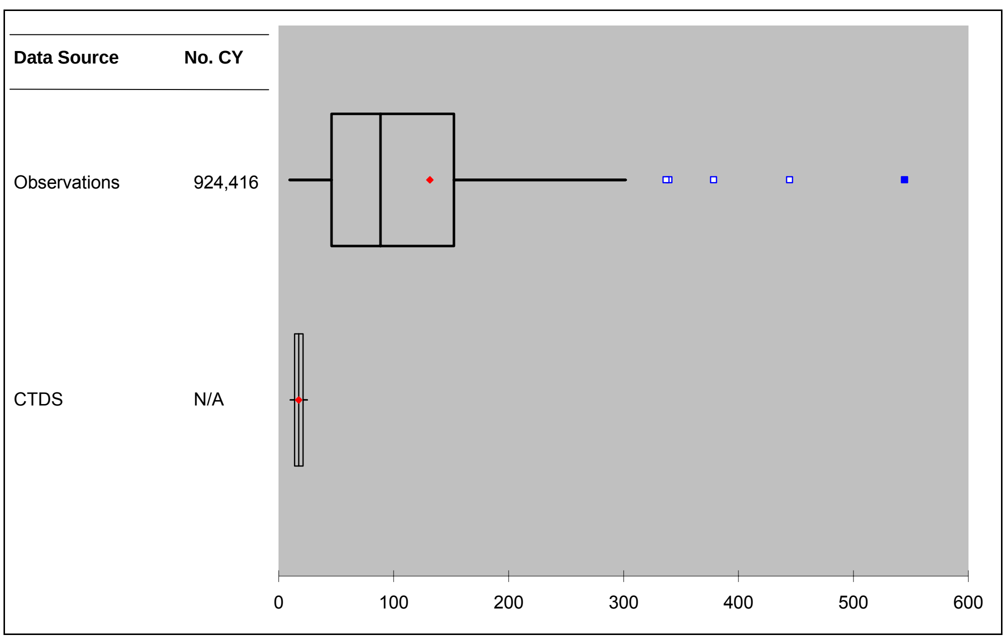


Figure 3.6: Box plots — CIP Concrete Box Culverts (cy/Crew Day)

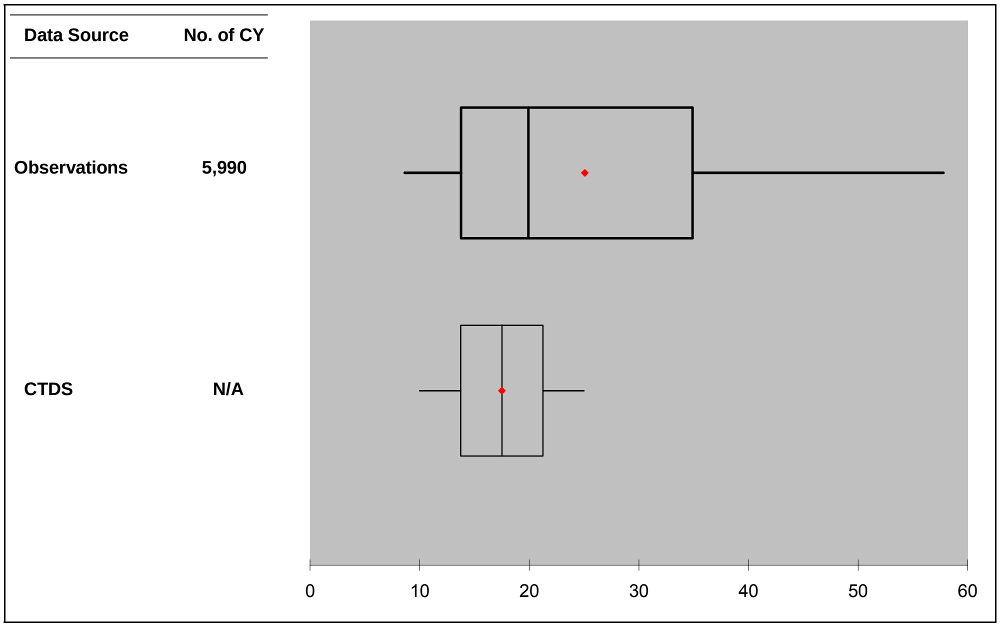


Figure 3.7: Box plots — Inlets and Manholes (ea./Crew Day)

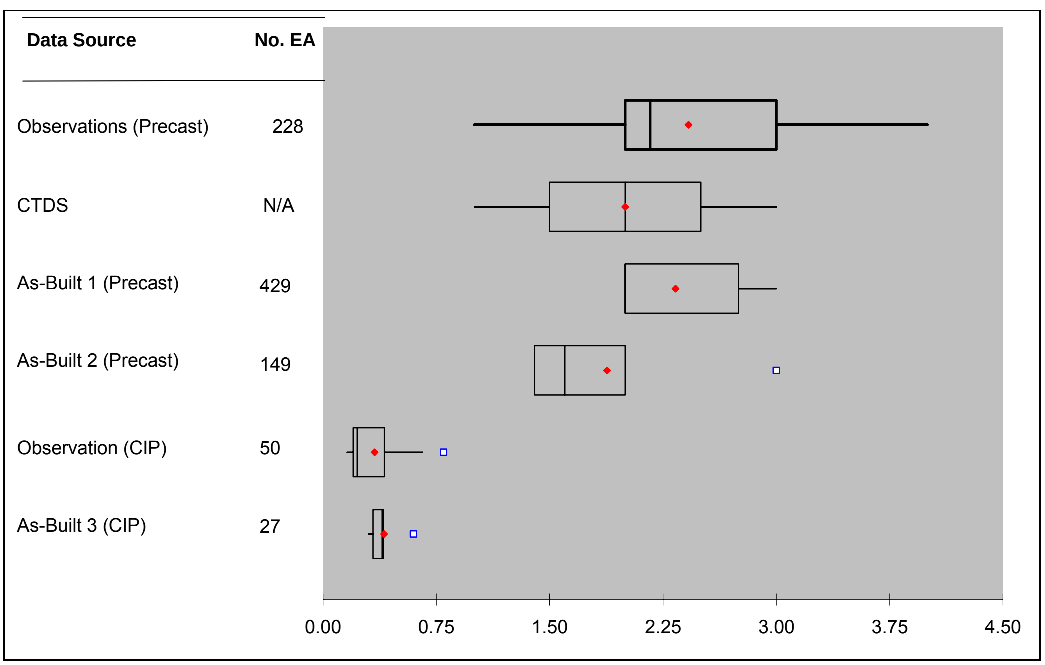
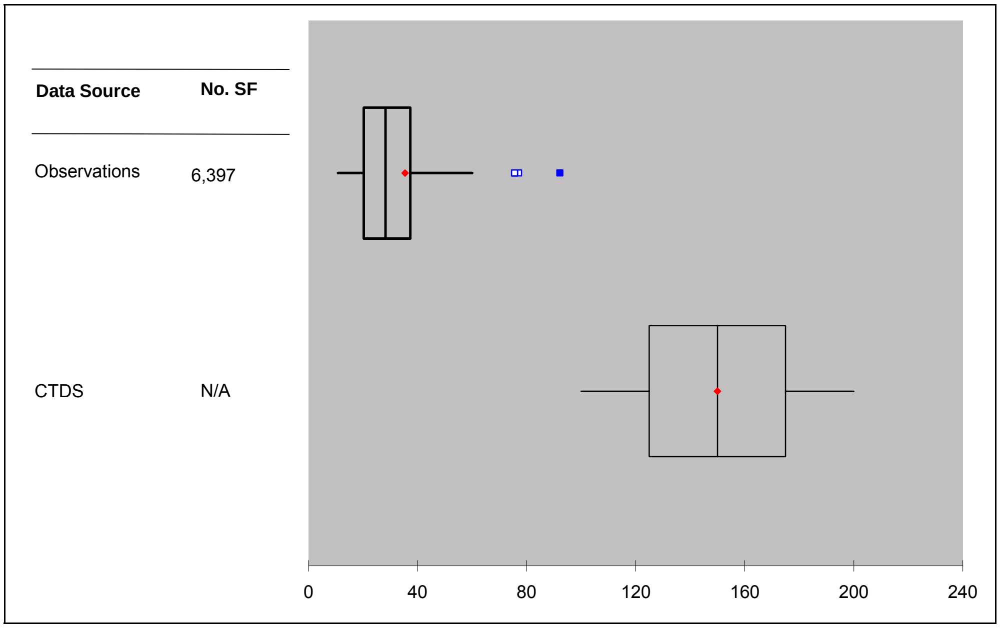


Figure 3.8: Box plots — Head Wall/Wing Wall (sf/Crew Day)



The following table summarizes the findings shown in the box-whisker plots.

Table 3.6: Production Rates - CTDS vs Observations

Item #	Work Item	Units Adopted by Research	P-value (Observed vs CTDS rates)	Field Research Production Rates Compared with CTDS Rates				
				Much Lower	Lower	Similar	Higher	Much Higher
409	Prestressed concrete piling	ea./crew day	0.004				√	
416	Drilled shaft foundation	lf/crew day	0.000	√				
423	MSE wall	sf/crew day	0.000					√
462-2	Cast in place concrete box culverts	lf/crew day	0.042				√	
464-1	RCP 18–42 in.	lf/crew day	0.000	√				
464-2	RCP 48–72 in.	lf/crew day	0.000	√				
465	Inlets and manholes	ea./crew day	0.204			√		
466	Wing wall/head wall	sf/crew day	0.000	√				

Table 3.7: Production Rates - CTDS vs As-builts

Item #	Work Item	Units Adopted by Research	P-value (Observed vs CTDS rates)	As-built Rates Compared with CTDS Rates				
				Much Lower	Lower	Similar	Higher	Much Higher
409	Prestressed concrete piling	ea./crew day	0.004				√	
423	MSE wall	sf/crew day	0.000					√
464-1	RCP 18–42 in.	lf/crew day	0.000	√				
464-2	RCP 48–72 in.	lf/crew day	0.000	√				
465	Inlets and manholes (Pre-cast)	ea./crew day	0.184			√		
465	Inlets and manholes (CIP)	ea./crew day	0.000	√				

Table 3.8: Production Rates - As-builts vs Observations

Item #	Work Item	Units Adopted by Research	P-value (Observed vs CTDS rates)	Field Research Production Rates Compared with As-built Rates				
				Much Lower	Lower	Similar	Higher	Much Higher
409	Prestressed concrete piling	ea./crew day	0.821			√		
423	MSE wall	sf/crew day	0.452			√		
464-1	RCP 18–42 in.	lf/crew day	0.625			√		
464-2	RCP 48–72 in.	lf/crew day	0.455			√		
465	Inlets and manholes (CIP)	ea./crew day	0.235			√		
465	Inlets and manholes (Pre-cast)	ea./crew day	0.877			√		

ANOVA test is used to examine the mean different between CTDS, as-built and observed rates. P-value for the ANOVA test is set at 0.1. The reason for adopting 0.1 is that construction productivity is influenced by many factors and highly variable, using a higher confidence interval helps incorporate such variances. The results of these tests are listed in Tables 3.6, 3.7, and 3.8.

As shown in Table 3.7, four items were found to have much lower rates, two had higher, one had much higher rates, and one with similar rates when comparing CTDS with the observed rates.

The analyses in Tables 3.7 and 3.8 show that there are significant differences between the CTDS and observed rates for most of the work items. Of the tested as-built production rates, all were found to be more similar to the observed rates than the CTDS rates. In addition, Figure 3.7 shows that CTDS rates seemed to be applicable only for pre-cast inlets and manholes and not for cast-in-place ones. Furthermore, ANOVA tests in Table 3.8 confirm that as-built and CTDS rates for pre-cast inlets and manholes are statistically similar but the rates for CIP ones are statistically different. On the other hand, the observed rates and as-built rates for both pre-cast and CIP inlets and manholes are similar. This suggested that new rates can be developed from the observed rates.

The analyses confirm the observed rates were more reliable and should be used to develop production rate models for the nine selected work items and new rates should be developed for two different types of MSE Wall components (copings and leveling pads), and CIP inlets and manholes.

CHAPTER 4 : ANALYSIS OF DRIVERS

This chapter discusses the methods that were used for production rate driver analyses. These analyses were used to identify significant production rate drivers and to establish and model the relationships between the production rates and the significant drivers.

4.1 IDENTIFYING SIGNIFICANT DRIVERS AND ESTABLISHING RELATIONSHIPS

Several statistical techniques were employed to identify relationships between candidate drivers and production rates.

The *t*-test for the analysis of variance (ANOVA) was used to test the differences between the mean production rates within each group of categorical or discrete candidate drivers. Due to similar reason as stated in Section 3.3, *p*-values obtained from the tests are set at 0.1. These values highlight the differences between the means for each group.

Nonlinear or linear regression analysis was also used to model the relationships between production rates and continuous numerical drivers. The logarithmic and power models were used to establish nonlinear relationships while simple regression models were used to establish linear relationship, between production rates and drivers. The R^2 and the adjusted R^2 of the linear, logarithmic, and power models were used to determine whether significant relationships existed between the drivers and the production rates. All applicable assumptions of the respective models were strictly complied with, and significant drivers that violated the assumptions were rejected.

Outlier analysis was also conducted, and all data points that were considered outliers were removed. Data that violated the assumptions for outlier, regression, and ANOVA analysis were rejected. Both the R^2 and p-values of these models had to be significant in order to ensure that developed models would be useful. Relying upon the suggestions provided by Green (1991), as shown in the table below, any model that had an R^2 value of equal or more than 0.26 and a p-value of less than 0.05 would be accepted as a sufficiently good model that could be used to estimate production rates. Weather impact on the observed production rates had been removed while the treatment of weather on the CTDS production rates was unknown.

4.2 ANALYSIS BY WORK ITEM

Detailed analyses were carried out according to the described statistical methods, and the results are presented according to work item number. The following table summarizes the analyses of all factors considered while following sections discuss results. Weather impact on the observed production rates had been removed while the treatment of weather on the CTDS production rates was unknown.

Table 4.1: Work Items and Drivers Relationships Findings

<table>
<tr><th rowspan="2">Drivers</th><th colspan="11">Work Items</th></tr>
<tr><th>409</th><th>416</th><th>423</th><th>423-1</th><th>423-2</th><th>462-1</th><th>462-2</th><th>464-1</th><th>464-2</th><th>465</th><th>466</th></tr>
<tr><th colspan="12">Project Level</th></tr>
<tr><td>Project Type</td><td colspan="11" rowspan="4">N</td></tr>
<tr><td>Location</td></tr>
<tr><td>Traffic Flow</td></tr>
<tr><td>Traffic Count</td></tr>
<tr><td>Weather (Precipitation)</td><td colspan="11">E</td></tr>
<tr><td>Weather (Winter Length)</td><td colspan="11" rowspan="3">N</td></tr>
<tr><td>% of Construction Completion</td></tr>
<tr><td>Contract Amount</td></tr>
<tr><td>Technical Complexity</td><td>N</td><td>Z</td><td colspan="7">N</td><td>Z</td><td>N</td></tr>
<tr><td>Contractual Drivers</td><td colspan="11" rowspan="9">N</td></tr>
<tr><td>Soil Types</td></tr>
<tr><td>Clay Content of Site</td></tr>
<tr><td>Land Slope of Site</td></tr>
<tr><td>Water Table Depth of Site</td></tr>
<tr><td>Scheduling Technique used</td></tr>
<tr><td>Work Schedule (Days/week)</td></tr>
<tr><td>Work Schedule (Hours/day)</td></tr>
<tr><td>Contract Administration System</td></tr>
<tr><th colspan="12">Work Zone Level</th></tr>
<tr><td>Work Zone Accessibility</td><td colspan="5">N</td><td>Y</td><td>Y</td><td colspan="4">N</td></tr>
<tr><td>Work Zone Construction Congestion</td><td colspan="11" rowspan="2">N</td></tr>
<tr><td>Work Zone Site Drainage Effectiveness</td></tr>
<tr><td>Clay Content of Soil</td><td colspan="7">N</td><td>Y</td><td colspan="3">N</td></tr>
<tr><td>Land Slope</td><td colspan="11">N</td></tr>
<tr><td>Water Table Depth</td><td colspan="2">N</td><td colspan="3">T</td><td colspan="6">N</td></tr>
<tr><th colspan="12">Work Item Level</th></tr>
<tr><td>Workmen Size</td><td colspan="11">N</td></tr>
<tr><td>Equipment Size</td><td colspan="11">N</td></tr>
<tr><td>Crew Size</td><td colspan="11">E</td></tr>
<tr><td>Equipment breakdown</td><td colspan="11">S</td></tr>
<tr><td>Utility Conflict</td><td colspan="2">E</td><td colspan="3">T</td><td colspan="4">E</td><td colspan="2">T</td></tr>
<tr><td>Construction Accident</td><td colspan="11">T</td></tr>
<tr><td>Incomplete Crew Size</td><td colspan="11">E</td></tr>
<tr><td>Work Zone/Item Quantity</td><td colspan="11">Z</td></tr>
<tr><td>Orientation</td><td colspan="5">N</td><td colspan="2">Y</td><td colspan="4">N</td></tr>
<tr><td>Materials/Types</td><td colspan="7">N</td><td colspan="2">Y</td><td colspan="2">N</td></tr>
<tr><td>Soil Type</td><td colspan="7">N</td><td>Y</td><td colspan="3">N</td></tr>
<tr><td>Location conditions</td><td>N</td><td>Y</td><td colspan="9">N</td></tr>
<tr><th colspan="12">Legend:</th></tr>
<tr><td colspan="12">Y = Yes, there is effect and factor is identified as significant</td></tr>
<tr><td colspan="12">N = No, factor is not significant</td></tr>
<tr><td colspan="12">E = Factor is significant but not useful for designers/planners</td></tr>
<tr><td colspan="12">S = Insufficient data point to prove relationship</td></tr>
<tr><td colspan="12">T = No such data collected</td></tr>
<tr><td colspan="12">Z = Yes, factor is significant but further breakdown and grouping is necessary</td></tr>
</table>

Data analysis indicated that there were six ways to categorize the relationship between drivers and work items: "Y" identified factors that were significant and useful; "N" for factors that were insignificant; "E" for factors that were significant but not useful for designers and planners; "S" for factors that had insufficient data points to prove any relationship; "T" for factors that had no data point at all; and "Z" identifies factors that had significant relationship but require further breakdown. Factors that fall under "N", "S", "T", and "E" were dropped. Factors that were identified as "Y" were selected for further analyses while those identified as "Z" were regrouped or redefined before further analyses were carried out. Only two factors fall under "Z" category. These factors include Technical complexity and Work zone/item quantity. Further analyses were carried out and the following definitions were adopted.

Table 4.2: Drivers' redefined

Work Item	**Original Driver Definition**	**New Driver Definition**
416	Technical Complexity	Location condition of operation
465		Types of Inlets/Manholes
409	Work Zone/Item Quantity	Total piles in cluster
416		Total shafts in cluster
423		Size of wall
423-1		Length of copings
462-1		Length of run
462-2		
464-1		
464-2		
465		Total quantity in run
466		Wall surface area

These redefined factors were selected for further analyses in the following sections.

4.2.1 Item 409: Prestressed Concrete Piling Foundations

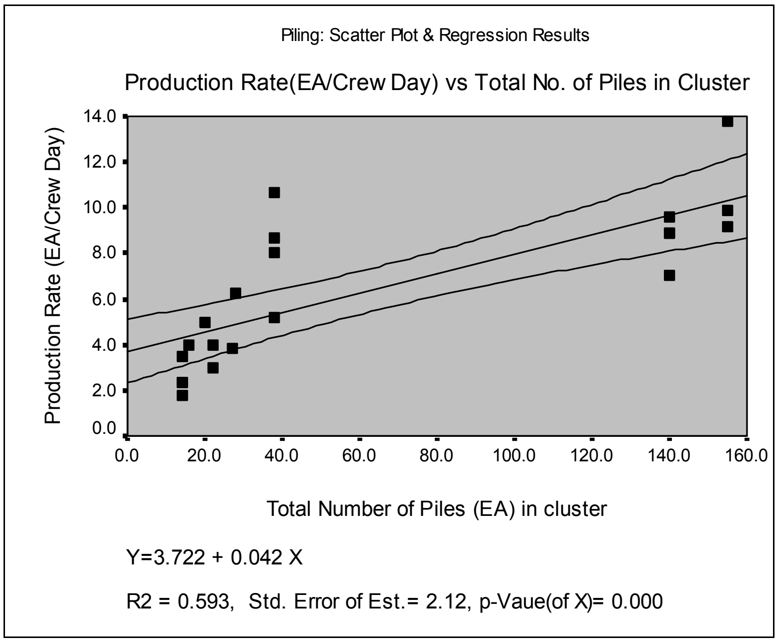
The "total number of piles where piles can be continuously installed" is found to be the only significant driver of piling production rates. In short, this driver is described as total quantity (ea.) of piles in a "cluster".

The linear model was found to have the best-fitting relationship between observed production rates and the total number of piles in a cluster. One data point was found to be an outlier and was removed from the regression analysis. The fitted linear model for piling installation is shown in the following figure. The model fell within the 99.9 percent confidence interval with an R^2 of 0.593. The coefficients of this model were statistically different from zero at the 99 percent confidence interval because the *p*-values of testing coefficients for the driver and constant term were less than 0.01.

This model is applicable only to pile cluster size between 13 and 152 ea. The estimated production rates of the fitted linear model range from 4.3 to 10.4 ea./crew day.

As observed in the linear model, two different groups were found to cluster at opposite ends. The first group involves a smaller number of piles within a cluster: between fifteen and forty piles. Whereas the second group involves a much higher number of piles within a cluster: between 140 and 158 piles. A second regression analysis was conducted to analyze the relationship between the total number of piles in the smaller cluster, but the second regression analysis was not done on the larger cluster because there was insufficient data.

Figure 4.1: Prestressed Concrete Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster]

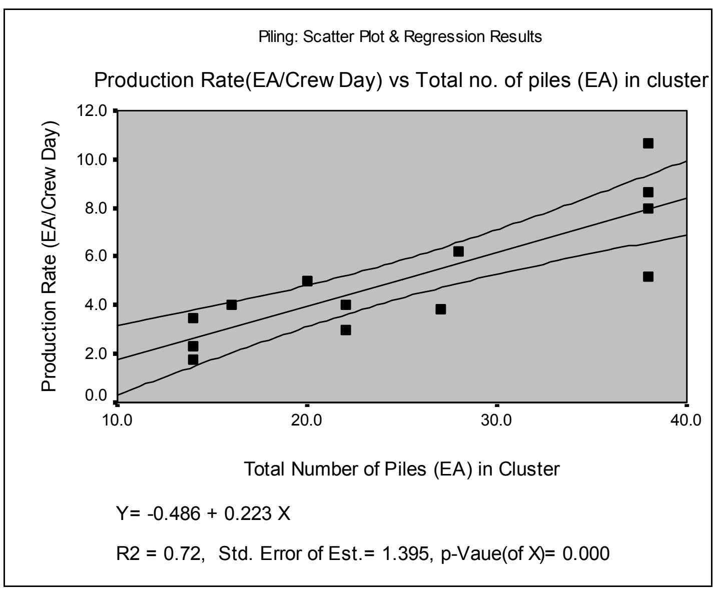


Smaller Cluster

Another model was developed for estimating production rates of the smaller cluster. The linear model was found to have the best-fitting relationship between observed production rates and the total number of piles in a cluster. One data point was found to be an outlier and was removed from the linear regression analysis. The fitted linear model for piling installation is shown in the following figure. The model falls within the 95 percent confidence interval with an R^2 of 0.72. The coefficients of this model were statistically different from zero at the 99 percent confidence interval, because the *p* values of testing coefficients for "total number of piles in a cluster" and constant term were less than 0.01.

This model is applicable only to cluster sizes within the range of 13 to 38 piles, because the data collected falls within this range. The estimated production rates of the fitted linear model range from 2.4 to 8.0 ea./crew day.

Figure 4.2: Prestressed Concrete Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster] for Small Pile Cluster



The higher R^2 value in the smaller pile cluster model suggests that it is a better model. Thus, it is suggested that this model be used to predict production rates for smaller pile clusters, whereas the former should be used to predict production rates of larger clusters.

4.2.2 Item 416: Drilled Shaft Foundations

Two production rate units were employed for drilled shaft foundations because both units appear to be useful for time estimation purposes. TxDOT uses three types of drilled shafts, cased, un-cased and cased with bentonite slurry and each type is used on specific soil conditions. Uncased drilled shaft is the most preferred construction method but it can only be applied on dry and stiff soils and is the most economical construction method. The cased method is used on soils that have constant contact with moisture while drilled shaft constructed in casing with bentonite slurry are used in extremely wet conditions. The result of t-test between production rates of cased and uncased drilled shafts showed that there is no significant difference between the production rates of the two construction methods. Thus, all of the drilled shafts were analyzed collectively.

Production Unit: lf/Crew Day

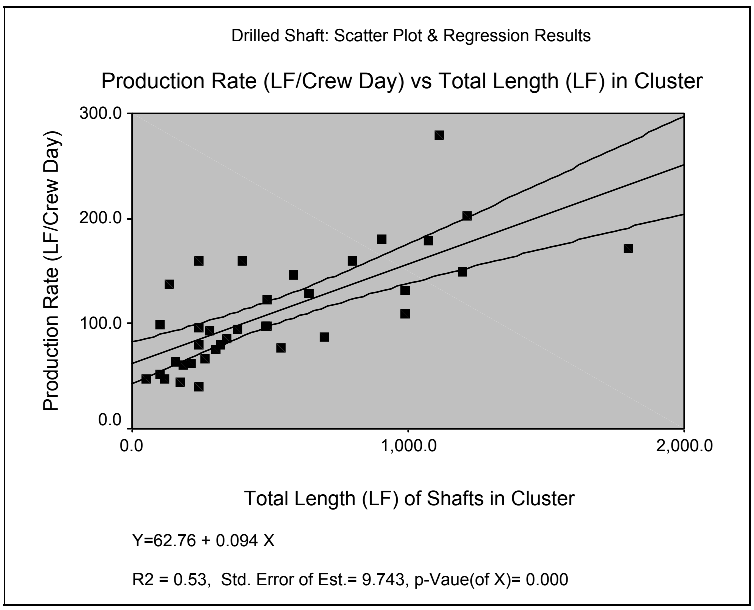
Using the production unit of lf/crew day, two significant drivers were found, Total length (ft) (in a cluster where drilled shafts can be continuously installed) and Location of operation.

Total Length (lf) in a Cluster

The linear model was found to best describe the relationship between observed production rates and the Total length of drilled shaft in a cluster. Two data points were found to be outliers and were removed from the regression analysis. The fitted linear model for drilled shaft foundations is shown in the following figure. The model fell within the 99.9 percent confidence interval with an R^2 of 0.593. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01.

This model is applicable only to drill shafts with a Total length in cluster between 50 and 1,800 lf. The estimated production rates of the fitted linear model range from 67 to 232 lf/crew day.

Figure 4.3: Drilled Shaft Foundations: Scatterplot [vs. Total Length of Shafts (lf) in Cluster]

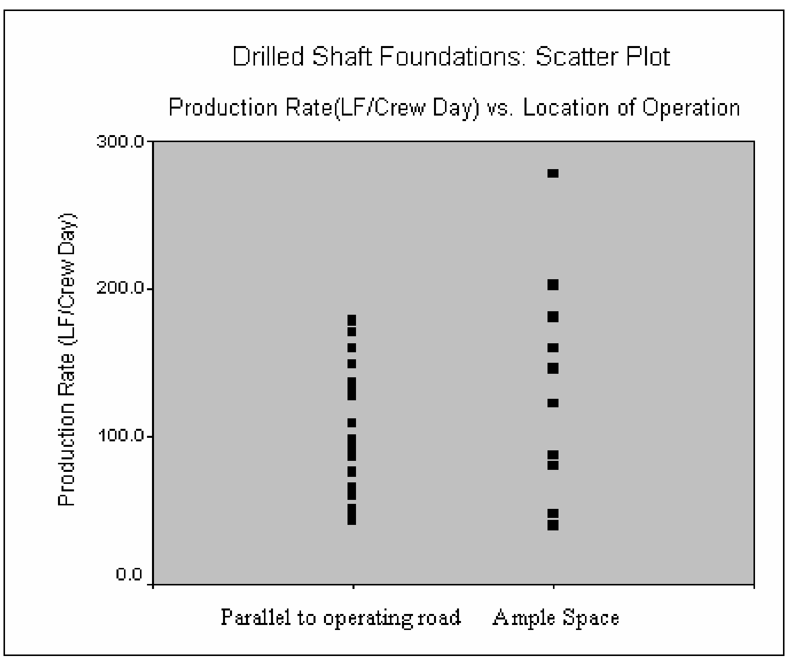


Location of Operation

Drilled shaft production rates were found to be driven by the location in which the operation took place. There are two categories in this driver: “ample space”, and “next to an operating road”. If the adjacent road next to the drilled shaft operations remained open during installation and the operations took place less than 20 ft. from that road, the data points were considered to be in the “next to an operating road” category. Otherwise, data points were considered to be in the “ample space” category.

The *t*-test was employed to test the difference in mean production rate between the two categories, because the two groups are independent and both groups are normally distributed. On the basis of the assumptions of equal variances between two groups, the *p*-value of the *t*-test was less than 0.1. Therefore, it can be concluded that the average production rates of Drilled shaft construction are different between the two categories at the 90 percent confidence interval. The average production rate for Drilled shafts built “beside an operating road” is 100 lf/crew day, and the mean production rate for Drilled shafts built with “ample space” is 133 lf/crew day. The difference between the two categories is 33 lf/crew day.

Figure 4.4: Drilled Shaft Foundations: Scatterplot (vs. Location of Operation)



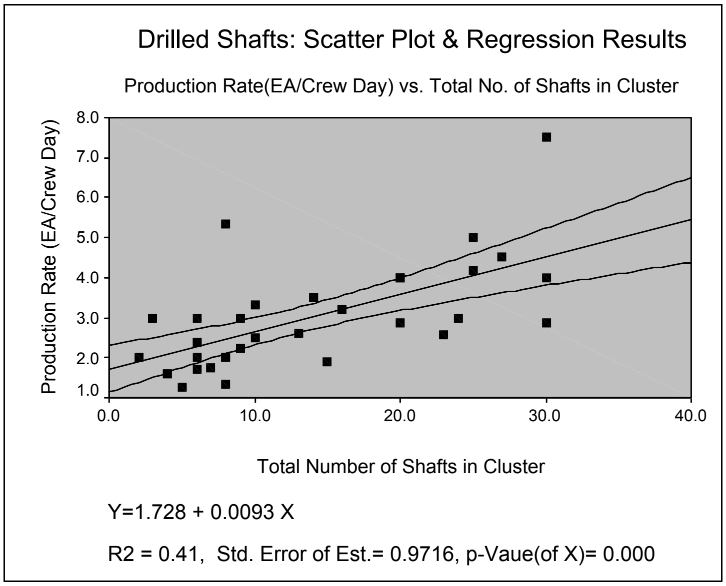
Production Unit: ea./Crew Day

Utilizing this alternate unit for Drilled shafts production rates, only one significant driver, Total number of shafts in a cluster, was found.

Total Number of Shafts in Cluster

The linear model was found to have the best-fitting relationship between e observed production rates and the Total number of drilled shafts in a cluster. Two data points were found to be outliers and were removed from the regression analysis. The fitted linear model for Drilled shaft foundations is shown in the following figure. The model falls within the 99.9 percent confidence interval with an R^2 of 0.41. The coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only for installing a drill shafts cluster of two to thirty shafts. Estimated production rates of the fitted linear model range from 1.8 to 2.6 ea./crew day.

Figure 4.5: Drilled Shaft Foundations: Scatterplot (vs. Total Number of Shafts in Cluster)



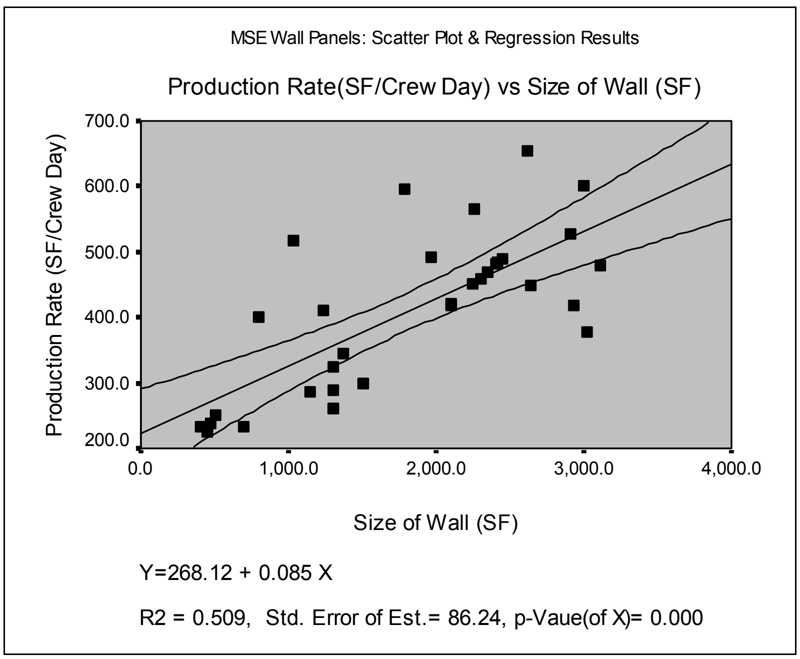
4.2.3 Item 423: Retaining Walls

While retaining walls can vary widely in configuration, because most retaining walls built by TxDOT are mechanically stabilized earth (MSE) walls, it was the only type of retaining wall investigated in this research. The tallest MSE wall section collected is 80 ft and the longest MSE wall section collected is about 0.25 mile long.

Only one factor, Size of wall, was found to be a significant driver for MSE walls. Size of wall is measured as the total surface area of a particular MSE wall, less areas of coping and leveling pad.

The linear model was found to have the best-fitting relationship between observed production rates and Size of wall. The fitted linear model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.51. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p*-values of the testing coefficients for the driver and the constant term were less than 0.01. This model is applicable only to walls between 430 and 3,400 sf. The estimated production rates of the fitted linear model can range from 305 to 557 sf/crew day.

Figure 4.6: Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Size of Wall (sf)]



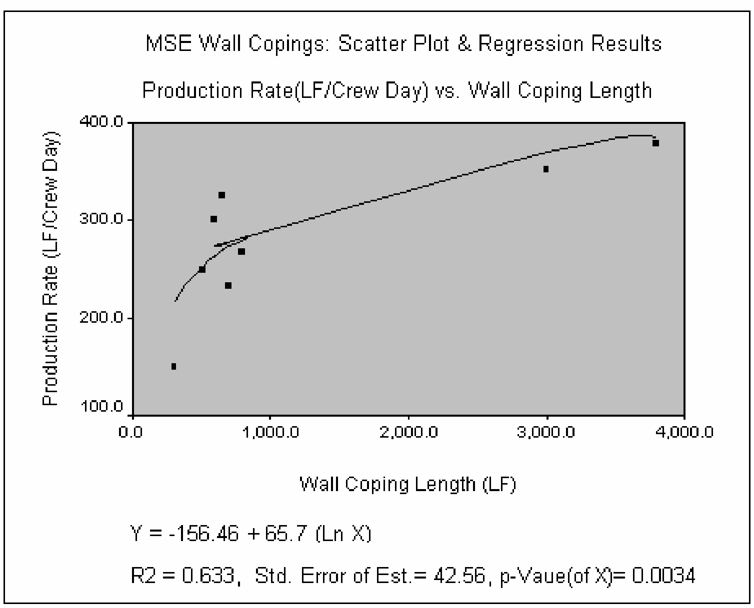
Production Rates of Copings, Footings, and Leveling Pads

The MSE wall production rate does not include the production of leveling pads, footings, and copings. Further investigation was carried out to determine the production rates of copings, footings, and leveling pads. These are discussed in the followings subsections.

Copings

Owing to the limited number of data points (eleven), the only significant driver found is the Length of coping. The logarithmic model was found to have the best-fitting relationship between observed production rates and Length of coping. The fitted logarithmic model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.633. This model is applicable only to coping lengths of 300 to 3,800 lf. The estimated production rates of the fitted logarithmic model range from 218 to 385 lf/crew day. The natural log is applicable to this formula.

Figure 4.7: Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Wall Coping Length (lf)]



Footings and Leveling Pads

The range of production rate was from 68 to 300 lf/crew day, and the mean was 178 lf/crew day. The longest footing and leveling pad observed was 800 lf, and the shortest was 160 lf. The minimum number of days used to construct the footings/leveling pads was two days, and the maximum was five days. It is recommended that estimators use two days for the shorter lengths, three to four days for the medium length ones, and five days for the long ones. Although one driver was found to be relatively significant, an attempt to place this driver on the regression plot found that the correlation coefficient (R^2) value was only 0.38, which is too low to confirm a relationship between production rate and the candidate driver. Moreover, the p-value was higher than the required 0.05, which indicates that the model did not lie within the required 95 percent confidence interval. Thus, no relationship is established.

4.2.4 Item 462: Concrete Box Culverts

Two types of concrete box culverts were studied in this research: cast in place and precast culverts.

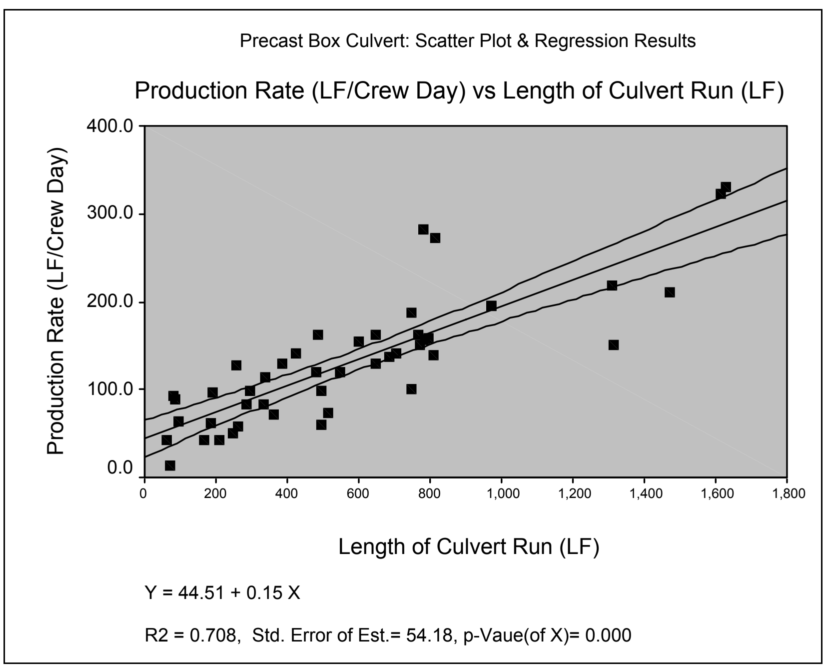
Precast Concrete Box Culverts

Three significant drivers — Length of culvert runs, Soil type, and Clay content in work zone — were found to be related to production rate.

Length of Culvert Runs

The linear model was found to have the best-fitting relationship between observed production rates and length of culvert runs. The fitted linear model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.708. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to wall sizes within ranging from 80 to 1,620 lf. Production can range from 12 to 243 lf/crew day.

Figure 4.8: Precast Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]

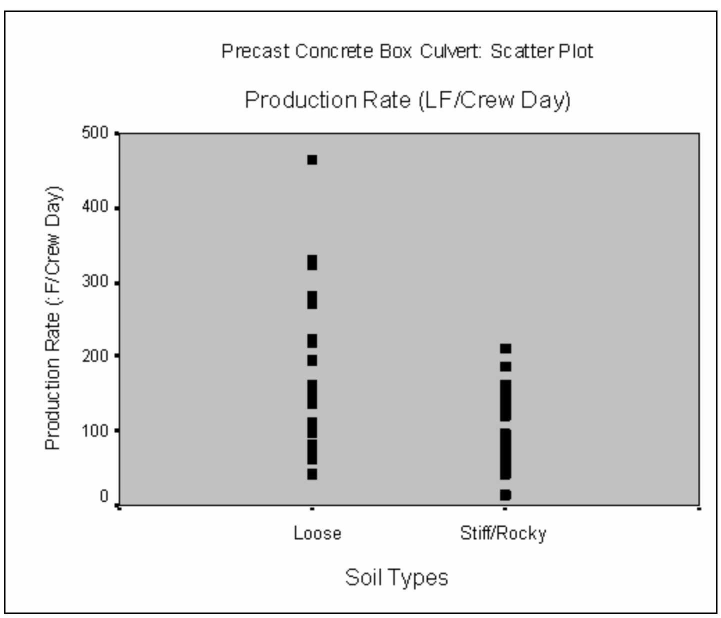


Soil Types

Stiffness of soil was found to affect the production rate of Precast concrete box culverts. The *t* test was employed to test the difference in mean production rate between loose and stiff soil. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rates of Precast culvert installation are different between the two soil categories at the 90 percent confidence interval.

The mean production rate for Precast culverts installation in Loose soil is 175 lf/crew day, and in Stiff/rocky soil it is 107 lf/crew day. The difference in mean production rate between the two soil categories is 68 lf/crew day.

Figure 4.9: Precast Box Culverts: Scatterplot (vs. Soil Types)

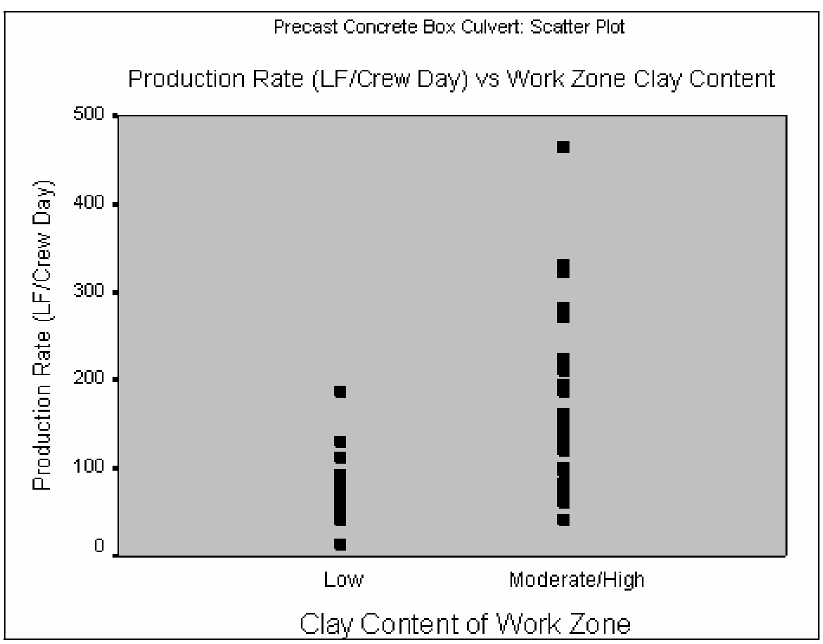


Soil Clay Content within Work Zone

The *t* test was employed to test the difference in mean production rate for Precast box culverts installed in soil of varying clay content. On the basis of the assumption of equal variances between two groups, the *p*-value of the *t* test was 0.001. Therefore, it can be concluded that the average production rates of Precast box culverts installation is influenced by soil clay content at the 90 percent confidence interval.

The mean production rate of Culverts in Moderate/high clay content soil is 167.5 lf/crew day, and mean production rate of culverts in Low clay content soil is 78.3 lf/crew day. The difference between the means is 89.2 lf/crew day.

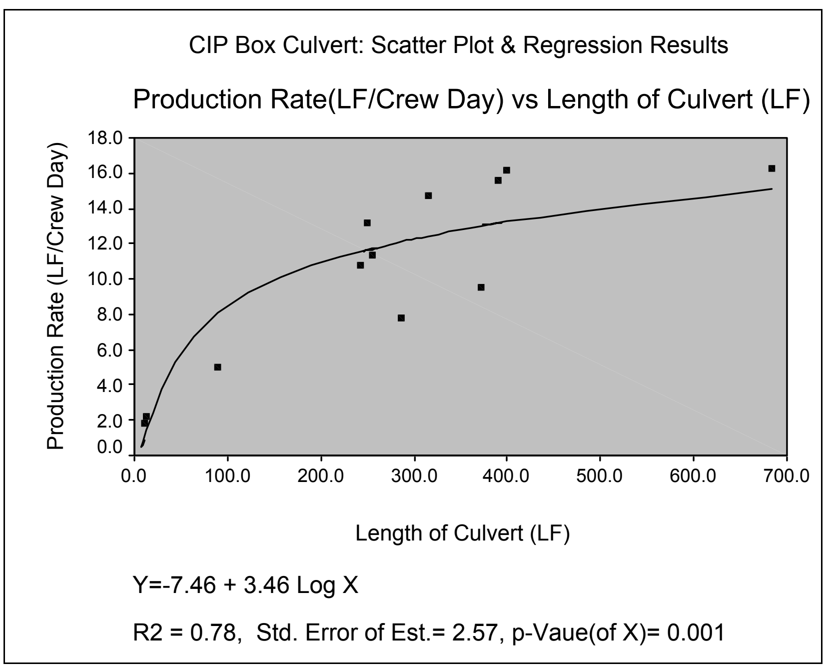
Figure 4.10: Precast Box Culverts: Scatterplot (vs. Clay Content on Work Zone)



Cast in Place Box Culverts

Length of box culvert was the only significant driver that drove the production rate of cast in place box culvert. A logarithmic relationship was found between Box culvert length and the production rates. The fitted model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.78. The coefficients of this model were statistically different from zero at the 95 percent confidence interval, and the *p*-value was less than 0.01. This model is applicable only for culvert lengths from 10 to 690 lf. The estimated production rates for the model range from 15.4 to 30.1 lf/crew day.

Figure 4.11: Cast in Place Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]



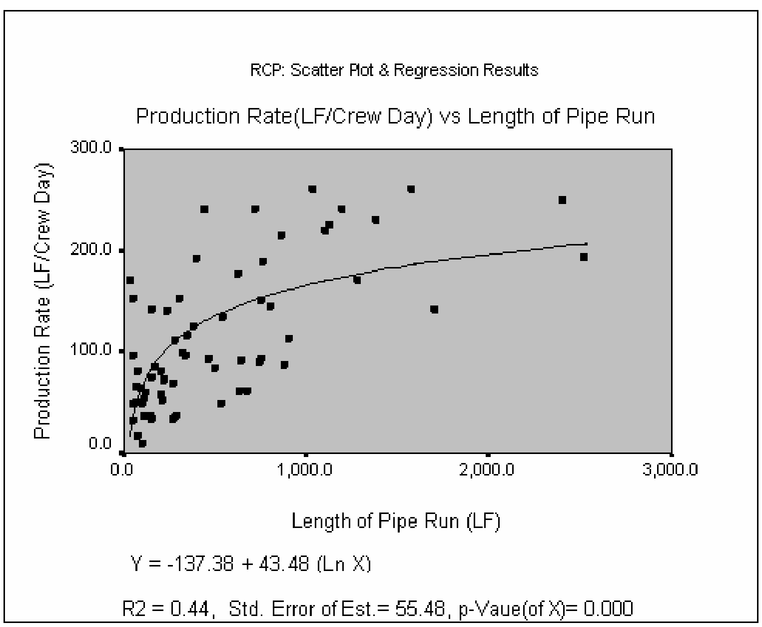
4.2.5 Item 464: Reinforced Concrete Pipes

Three drivers: Length of pipe run, Line orientation, and Work zone accessibility — were found to have significant impacts on Reinforced concrete pipes (RCP) production.

Length of Pipe Run

The logarithmic model was found to have the best-fitting relationship between observed production rates and Length of pipe run. The fitted linear model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.44. This model is applicable only to Length of pipe run from 68 to 2,600 lf. Estimated production rates of the fitted logarithmic model range from 46.1 to 204.5 lf/crew day.

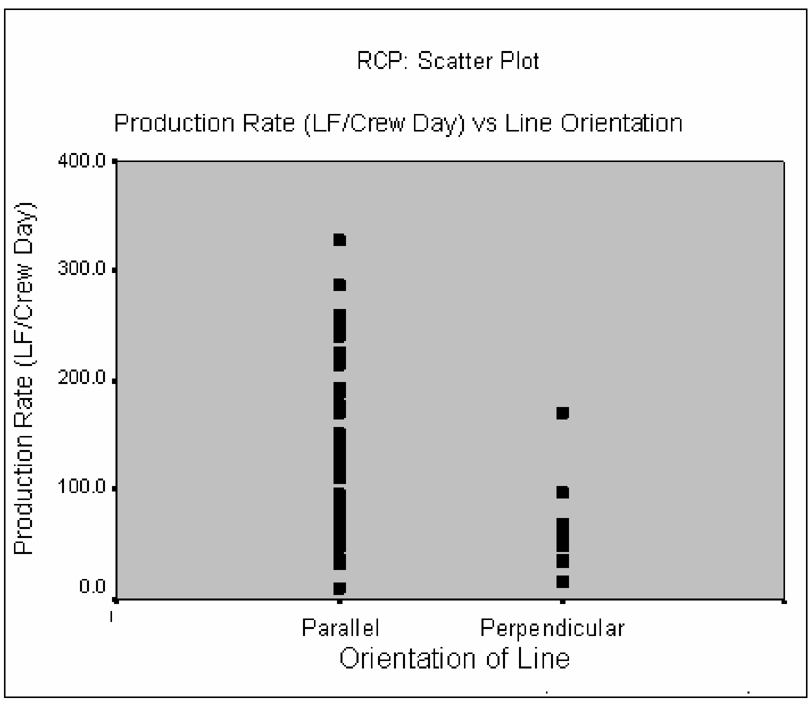
Figure 4.12 Reinforced Concrete Pipe: Scatterplot and Regression Results [vs. Length of Pipe Run (lf)]



Line Orientation

Direction of the pipe run was found to be an important production rate driver. When a pipe runs parallel to a road, the operation meets a more consistent terrain and soil surface and thus production rates are expected to be higher. But when pipe runs perpendicular to the road, the operations are less consistent owing to surface differences and increased likelihood of meeting a hard surface or old pipes. Thus, lower production rates are expected.

Figure 4.13: Reinforced Concrete Pipe: Scatterplot (vs. Orientation of Line)



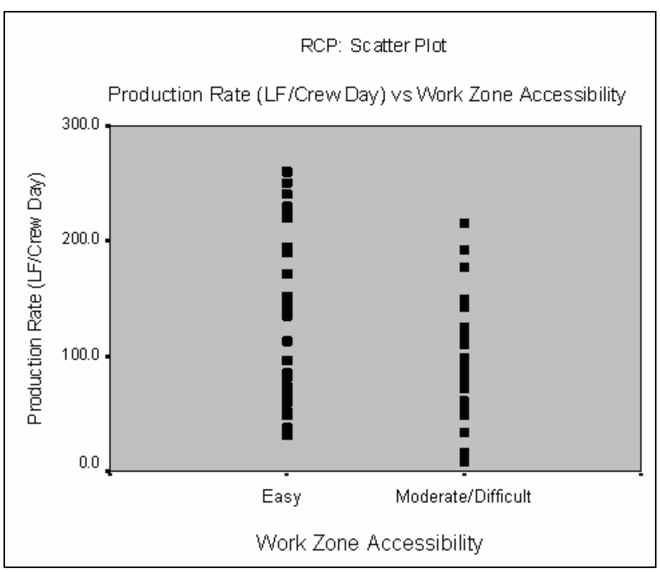
The *t*-test was employed to test the difference in mean production rate between the two line orientations. The average production rates of pipe installation were significantly different between the two categories at the 90 percent confidence interval.

The mean production rate for pipes installed parallel to the road is 136 lf/crew day, and the mean production rate for pipes installed perpendicular to the road is 75 lf/crew day. The difference of means is 61 lf/crew day.

Work Zone Accessibility

The *t*-test was employed to test the difference in mean production rate between different levels of work zone accessibility. The mean production rate of pipe installation was found to be different between the two work zone categories at the 90 percent confidence interval.

Figure 4.14: Reinforced Concrete Pipe: Scatterplot (vs. Work Zone Accessibility)



The mean production rate for pipe installation in work zone of moderate/difficult accessibility is 104.5 lf/crew day, and the mean production rate in work zone of easy accessibility is 135.2 lf/crew day. The difference between the means is 30.8 lf/crew day.

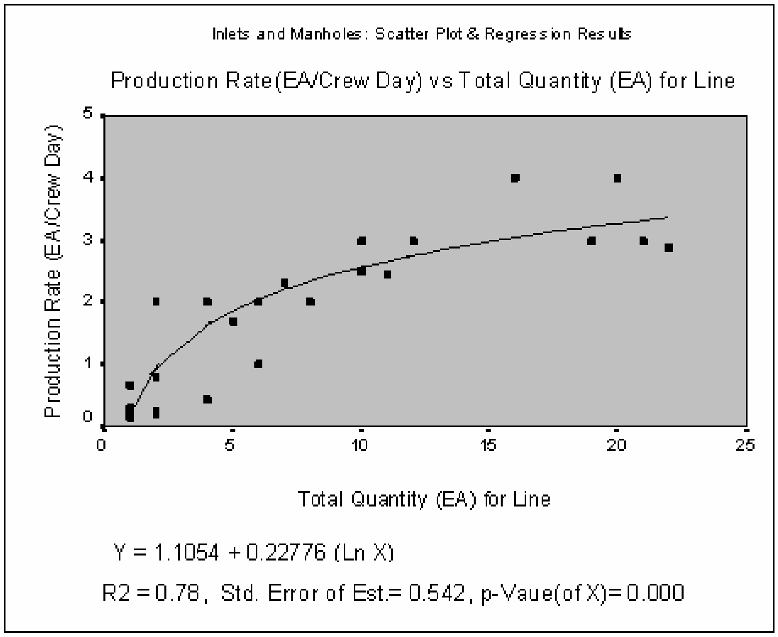
4.2.6 Item 465: Inlets and Manholes

Three factors were found to significantly drive the production rates of Inlets and manholes. These drivers were Total quantity (ea.) of inlets/manholes for line, Inlets with manholes installation or Manholes installation only, and Cast in place versus Precast.

Total Quantity (ea.) of Inlets/Manholes for Line

The logarithmic model was found to have the best-fitting relationship between observed production rates and Total quantity (ea.) of Inlets and/or manholes for line. The fitted linear model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.78. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the p values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to number of inlets/manholes for line from 1 to 23. Estimated production rates of the model range from 1.1 to 4.2 inlets/manholes per crew day.

Figure 4.15: Inlets and Manholes: Scatterplot [vs. Total Quantity (ea.) for Line]

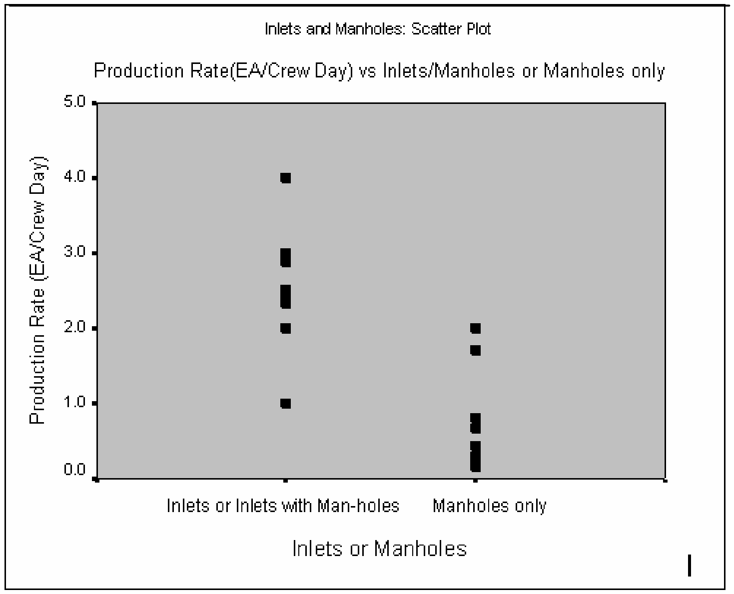


Inlets/Manholes or Manholes Only

The *t*-test was employed to test the difference in mean production rate between installation of Inlets/manholes or Manholes alone. On the basis of the assumption of equal variances between the two groups, the *p*-value of the *t*-test was less than 0.1. Therefore, it can be concluded that the average production rate of Inlets and manholes is different between the two categories at the 90 percent confidence interval.

The mean production rate of Inlets or inlets with manholes installation is 2.5 per crew day, and the mean production rate for Manholes only installation is 0.874 per crew day. The difference of mean production rate between the two categories is 1.7 per crew day.

Figure 4.16: Inlets and Manholes: Scatterplot (vs. Inlets or Manholes for Line)

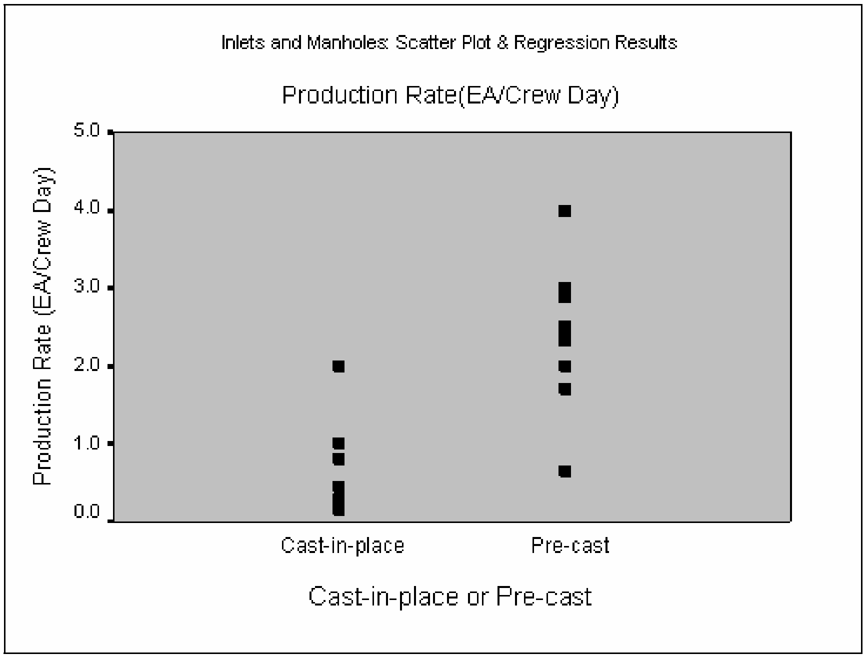


Cast in Place or Precast

The *t*-test was employed to test the difference in mean production rate between Cast-in-place or Precast inlets and manholes. On the basis of the assumption of equal variances between two groups, the *p*-value of the *t*-test was less than 0.1. Therefore, it can be concluded that the average production rates of Cast-in-place and Precast inlets and manholes were different between the two categories at the 90 percent confidence interval.

The mean production rate for Cast-in-place inlets and manholes is 0.8 per crew day, and the mean production rate of Precast manholes and inlets is 2.52 per crew day. The difference of mean production rate between the two categories is 1.8 per crew day.

Figure 4.17: Inlets and Manholes: Scatterplot (vs. Cast in Place or Precast)

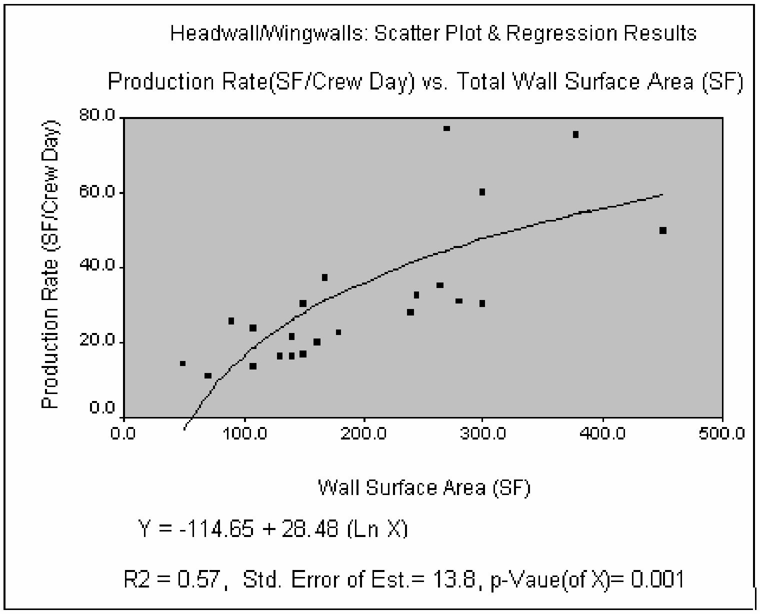


4.2.6 Item 466: Head Walls and Wing Walls

For Head walls and wing walls, only one driver, Total wall surface area, was found to have a significant effect on production rates.

The logarithmic model was found to have the best-fitting relationship between observed production rates and Wall surface area. The fitted logarithmic model for this driver is shown in the following figure. The model fell within the 95 percent confidence interval with an R^2 of 0.61. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p*-values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to Wall sizes from 70 to 480 sf. The estimated production rates of the model range from 6.4 to 61.2 sf/crew day.

Figure 4.18: Head Walls/Wing Walls: Scatterplot [vs. Wall Surface Area (sf)]



4.3 MULTIPLE REGRESSIONS

The effects of multiple drivers can cause production rates to vary. In this section, multiple regression models that result from combining significant drivers are discussed.

Multiple regressions models were not developed for work items with insufficient data points. The minimum number of data points was based on the suggested values provided by Green (1991).

Correlations were tested between significant drivers. When factors were correlated, the model with the highest R^2 value and lowest *p*-value for each factor was chosen as the representative model for the selected work items. The data were tested for all assumptions and possible violations prior to the multiple regression analyses being carried out.

4.3.1 Item 416: Drilled Shaft Foundations

The two significant drivers found for drilled shafts — Location of work operation and Total length of shafts in cluster — were used for multiple regression. Two data points were found to be outliers and were removed from the multiple regression analysis. The different categories for Location of work operation were transformed into binary values. Parallel to an operating road was recoded as 0, and ample space was recoded as 1.

The fitted model, shown in the following equation, was statistically significant at the 95 percent confidence interval with an R^2 of 0.567. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the p-values of the coefficients for Location of work operation and the constant term were less than 0.05.

$$\text{Production Rate} = 56.91 + 0.00903 * (\text{TLC}) - 22.756 * (\text{LWO}) \tag{4.3}$$

TLC = Total length of shafts in cluster (lf.)

LWO = Location of work operation

This model is applicable only for TLC within the range of 50 to 1,870 lf. The estimated production rates of this model range from 34.6 to 73.2 lf/crew day.

4.3.2 Item 462: Precast Concrete Box Culverts

Three significant drivers were found for Precast concrete box culverts. Attempts to combine the effects of all three significant drivers failed because the *p*-values for one of the drivers did not fall within the required 90 percent confidence interval. As a result, only two significant drivers were used to develop each model. Two models were found to be statistically significant.

First Model: Total Length of Pipe Run (lf) and Clay Content in Soil

No data points were found to be outliers. The different Clay content categories were transformed into binary values. Low clay content was recoded as 0, and High/moderate clay content was recoded as 1.

The fitted model, shown in the following equation, was statistically significant at the 95 percent confidence interval with an R^2 of 0.667. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval with *p* values of the coefficients less than 0.05.

$$\text{Production Rate} = 37.087 + 0.1 * (\text{TRC}) + 48.93 * (\text{CC}) \qquad (4.4)$$

TRC = Total length of culvert run (lf)

CC = Clay content

This model is applicable only for TRC within the range of 80 to 1,620 lf. The estimated production rates of this model range from 45.1 to 248.0 lf/crew day.

Second Model: Total Length of Pipe Run (lf) and Soil Types

Four data points were found to be outliers and were removed from the data. The categories for Soil types were transformed into binary values. Loose soil was recoded as 0 and Stiff/hard Soil was recoded as 1.

The fitted model, shown in the following equation, was statistically significant at the 95 percent confidence interval. The R^2 was 0.55. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the *p*-values of the coefficients were less than 0.05.

$$\text{Production Rate} = 86.845 + 0.104 * (\text{TPR}) - 35.562 * (\text{ST}) \tag{4.5}$$

TPR = Total length of pipe run (lf)

ST = Soil type

This model is applicable only for TPR the range of 80 to 1,620 lf. Therefore, the estimated production rates of this model range from 59.6 to 255.3 lf/crew day.

4.3.3 Item 464: Reinforced Concrete Pipes

Attempts were made to build multiple regression models using the three significant factors for Reinforced concrete pipe. However, only the coefficients of two significant drivers — namely, Total quantity (lf) of pipe run and Work zone accessibility — were found to fall within the 90 percent confidence interval, and thus only two significant drivers were applied to the model.

Two data points were identified as outliers and were removed from the data. The categories for Work zone accessibility were transformed into binary values. Easy work zone accessibility was recoded as 0, and Moderate/difficult was recoded as 1.

The fitted model, shown in the following equation, was statistically significant at the 95 percent confidence interval with an R^2 of 0.432. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the *p*-values of coefficients for Location of work operation and the constant term were less than 0.1.

$$\text{Production Rate} = -126.22 + \text{Log}_{10} 103.558 * (\text{TPR}) - 27.932 * (\text{WZA}) \qquad (4.6)$$

TPR = Total quantity of pipe run (lf)

WZA = Work zone accessibility

This model is applicable only for TPR within the range of 68 to 2,600 lf. Therefore, the estimated production rates of this model range from 28.0 to 227.4 lf/crew day.

All the multiple regression formulas are summarized in the following table.

Table 4.3: Summary of Formulas and Ranges of Application

Item #	Work Item	Factor	Formula (Production Rate)	Applicable Range
409	Prestressed concrete piling	Total number of piles in cluster	3.711 + 0.042 X	13–152 ea.
416	Drilled shaft foundation	Total length in cluster	62.76 + 0.094 X	50–1,800 lf
423	MSE wall	Size of wall	268.12 + 0.085 X	430–3,400 sf
423-1	MSE wall — copings	Length of coping	−156.46 + 65.7 Ln X	300–3,800 lf
462-1	Precast concrete box culverts	Length of culvert run	44.51 + 0.15 X	80–1,620 lf
462-2	Cast in place concrete box culverts	Length of culvert run	−7.46 + 3.46 Ln X	10–690 lf
464-1	Reinforced concrete pipe	Length of pipe run	−137.38 + 43.48 Ln X	68–2,600 lf
465	Inlets and manholes	Total number of inlets/manholes in line	1.1054 + 0.2276 Ln X	1–23 ea.
466	Wing wall/head wall	Wall surface area	−114.65 + 28.48 Ln X	70–480 sf

4.4 SUMMARY OF DRIVERS AND FORMULAS

The above table suggests some similarities between the drivers considered by CTDS and those found in this research. The descriptions for the drivers adopted by CTDS are not as clear, however. For example, for excavation, quantity of work is a driver for CTDS, but it does not clearly specify whether the quantity of work refers to the quantity for the entire project or a given work zone. ANOVA analysis found that quantity in the work zone drives the production rate and quantity for the entire project does not. In another example, one of the drivers for RCP found in CTDS is “location”.

This research defined location more narrowly and found that Work zone accessibility and Line orientation better describe relevant location conditions.

Table 4.4: Summary of Drivers of CTDS and Research

Item #	Work Item	Sensitive Factors CTDS Considered	Sensitive Factors the Research Found
409	Prestressed concrete piling	Soil	Total piles in cluster
416	Drilled shaft foundation	Soil	Total shafts in cluster, location conditions of operation
423	MSE wall	Soil	Size of wall
423-1	MSE wall — copings	—	Length
462-1	Precast concrete box culverts	Soil	Length of run, soil types, clay content
462-2	Cast in place concrete box culverts	Soil	Length of run
464-1	RCP 18–42 in.	Location, soil	Length of run, WZA**, line orientation
464-2	RCP 48–72 in.	Location, soil	
465	Inlets and manholes	Location, soil	Total quantity in run, types
466	Wing wall/head wall	Soil	Wall surface area

**WZA, work zone accessibility

However, some differences between driver relationships were also found. For example, although soil is considered within CTDS to be one of the drivers for foundation construction, the research found (perhaps surprisingly) that all of the drivers for foundations turned out to be unrelated to soil. Although soil is generally perceived to be a driver of foundation production rate, the research found that the presence of other, more significant drivers reduced the significance of soil as a driver.

In summary, the research confirmed many but not all drivers identified by CTDS and suggested others. These results should allow estimators to develop more accurate production rates for these work items.

4.5 PREDICTING PRODUCTION RATES USING THE DRIVERS AND FORMULAS

This research developed some useful information for construction time estimation. Estimators can apply this information to develop practical and useful production rates. At the same time, they should apply their experience and judgment to adjust the calculated production rates according to specific project conditions that they may be more familiar with.

The estimator can rely on any of the information in the following tables, to determine realistic production rates. For example, if a designer plans for an 800 lf culvert in stiff, rocky soil, the estimated production rate based on that condition is 164.51 lf/crew day and the mean production rate for culvert construction on stiff/rocky soil is 107 lf/crew day. The estimator can also rely on multiple regression formulae to calculate expected production rates. Using the multiple regression formula with the combined effects of Length of culvert run and Stiff/rocky soil, the calculated production rate is 117.1 lf/crew day.

Also as an example, the calculated production rate ranges from a low of 107 lf/crew day when the full impact of Soil condition is considered, to a high of 164.51 lf/crew day, when the impact of Soil is not considered. The estimator should use his/her personal experience to make the best estimation, given the project environment.

Factors that the estimator finds to be applicable to the production operation, such as crew productivity and regional adjustments, should be used to adjust calculated production rates. The estimator can also determine whether the project requires a faster or slower completion time. If schedule is accelerated, 117 lf/crew day may be applicable, otherwise 107 lf/crew day may be considered appropriate.

However, the estimators should note that the suggested production rates are applicable only to one run of culvert. Because different culvert runs have different lengths, each run may have a different production rate.

Table 4.5: Summary of Discrete Drivers and Range of Production Rates

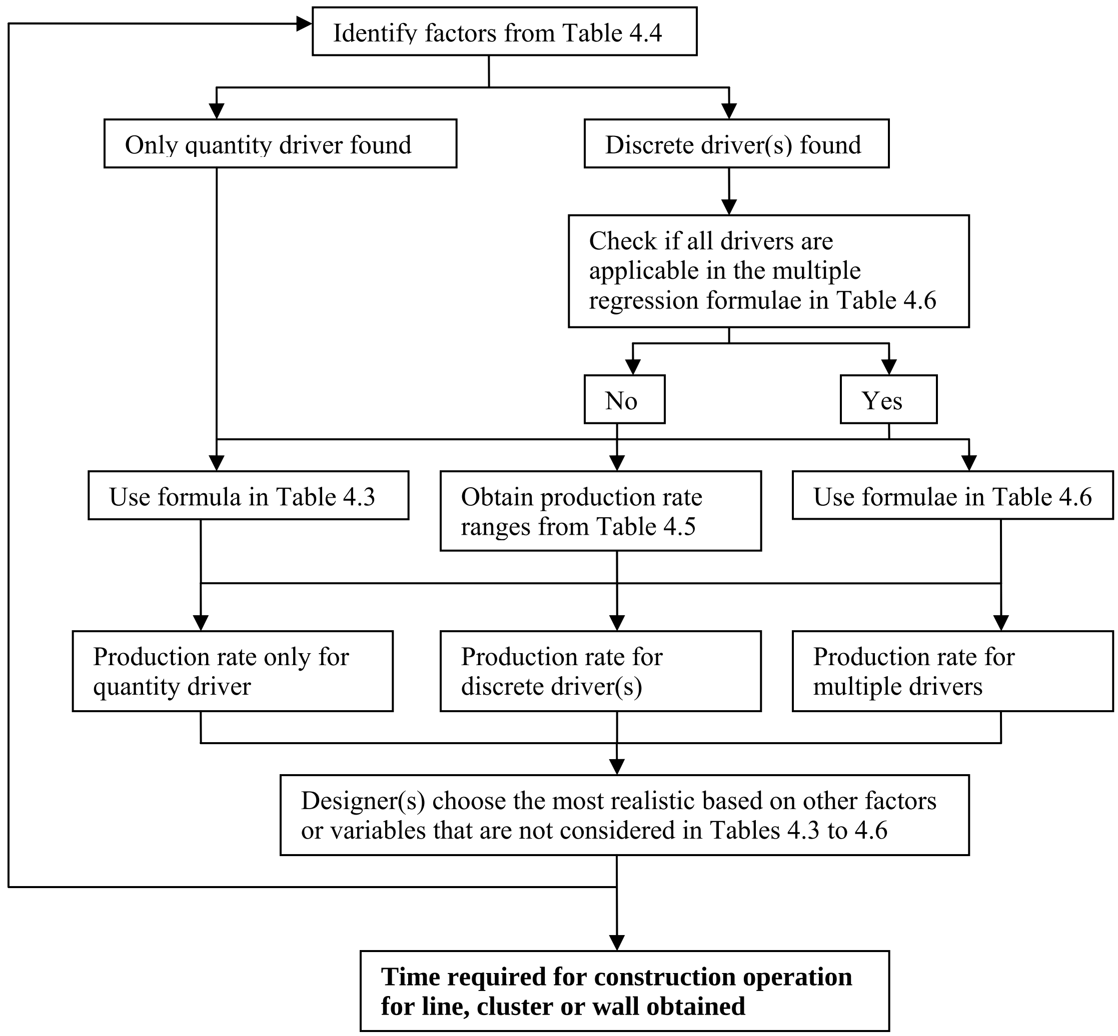
Item #	Work item	Factor	Unit	Lowest Average of Production Rate	Mean Production Rate	Highest Average of Production Rate
416	Drilled shaft foundation	Location of operation	lf/crew day	100	111	133
462-1	Precast concrete box culverts	Soil types	lf/crew day	107	138	175
		Clay content	lf/crew day	78.3	123.9	167.5
464	Reinforced concrete pipe	Line orientation	lf/crew day	75	107.2	136
		Work zone Accessibility	lf/crew day	104.5	122.4	135.2
465	Inlets and manholes	Inlets or manholes	ea/crew day	0.874	1.89	2.53
		Cast in place or precast	ea/crew day	0.768	1.56	2.52

Table 4.6: Summary of Formulas and Ranges of Application for Multiple Regressions

Item #	Work Item	Production Rate Formula	Applicable Range
416	Drilled shaft foundation	Production rate = 56.91 + 0.00903 × (total length of shafts in cluster) − 22.756 × (location of work operation)	50–1,800 lf
462-1	Precast concrete box culverts	Production rate = 37.087 + 0.1 × (total length of culvert run [lf]) + 48.93 × (clay content)	80–1,620 lf
		Production rate = 86.845 + 0.104 × (total length of pipe run [lf]) − 35.562 × (soil types)	10–690 lf
464	Reinforced concrete pipe	Production rate = −126.22 + Log$_{10}$ 103.558 × (total quantity [lf] of pipe run) − 27.932 × (work zone accessibility)	68–2,600 lf

Figure 4.19 illustrates a suggested process for estimating production rates and construction time of different work items.

Figure 4.19 Production rate estimation process



4.6 IMPACT OF DISRUPTION ON PRODUCTION RATES

In general, disruptions can cause two types of delays. First, production may be stopped during the period of disruption and results in delay. Second, productivity of resumed production after a disruption may be slower than production prior to disruption. Such reduction in productivity after production resumes is usually not accounted for in most time delay claims but can significantly impact overall project productivity.

The production rate calculation method adopted by this research eliminated effects of disruption on production rate due to work stoppage, but the calculation method does not address production rates recovery after disruption. There were many different types of disruptions found during data collection. These disruptions include shortages of materials, labor and equipment, equipment breakdown, utility conflict, change orders, poor planning (extensive relocation of equipment), and rain.

Production usually stops during a disruption. Production rates collected for this research that were affected by delays and stoppage have been adjusted using the "half-day" rule as discussed in Section 2.23 and Table 2.6. As a result of the adjustment, the models and rates listed in Tables 4.3, 4.5 and 4.6 apply to "working days" production rates only. Due to the wide variety of causes and drivers of causes, it is not possible to estimate total stoppage days due to disruption. For example, the number of stoppage days due to disruption from rain and utility conflicts depends on factors beyond the control of contractors and designers. Working project schedules need to be adjusted for such disruptions but this is beyond the scope of this research. Thus, production stoppage prediction or measurement due to disruption is not a part of this research.

In addition, different contractual agreements, most prominently Working Day and Calendar Day contracts, impose different production obligations on contractors and influence the ways contractors and TxDOT treat operation days. ANOVA tests show insignificant differences between production rates of Working day and Calendar day contracts for six work items (p-values between 0.13 and 0.76, and the other three work items do not have data from Calendar day contract).

Thus, this research does not analyze disruption due to production stoppage and production rate differences between Working Day and Calendar Day contracts.

However, production before and after disruptions was measured and compared to determine the impact of learning curves and rates of production recovery. The method used to measure baseline production rate is similar to the production rate measurement method adopted by this research and shown in Sections 4.1, 4.2 and 4.3. Each operation has its own baseline production rate and each rate was benchmarked as 100% with rates after production resumes (called recovered production rate) being expressed as percentages of respective baseline rates. *T test* is used to examine statistical differences between means of recovered production rates and means of baseline rates.

In contrast, *t tests* conducted on disrupted and baseline rates for reinforced concrete pipe (RCP) and pre-cast concrete box culvert (PCB) affected by rain on soil with different clay content were found to have significant differences. Further analysis found that production carried out after rain on soil with high clay content were significantly slower than on soil with low clay content. Some clays expand when exposed to moisture and moist clay is very difficult to work on. Work items, like RCP and PCB, that are in frequent contact with clayey soils are more likely to be affected by rain when production resumes. The analysis in the following section found that production rates were affected for up to three days, with such impact yielded lower overall production rates. Though Clay content in soil was not a driver as discussed in Sections 4.2 and 4.3, this section confirms that Clay content in soil becomes a driver when moisture comes into play.

4.6.1 Effects of Rain on Soil with Different Clay Content in RCP and PCB construction

A total of 106 raining incidents were recorded. Of these 48 incidents occurred on soil with high clay content, 30 on soil with medium clay content, and 28 on soil with low clay content.

Production Recovery after rain on different soil types: Soils with Low Clay Content

The p-values in Table 4.7 show that production rates were significantly different between first and second day, and second and third day. The p-values in Table 4.8 show that production on soils with low clay content resumed quicker than in soils with medium and high clay contents.

Production Recovery after rain on different soil types: Soils with Medium Clay Content

The p-values in Table 4.8 suggest that production rates were significantly different between first and second day but differences were not significant between second and third day. These results suggest that production recoveries are considerably slower in soil with medium clay content than for soil with lower clay content.

Production Recovery after rain on different soil types: Soils with High Clay Content.

The p-values in Table 4.8 also indicate that production rates were only significantly different on the second and third day. These results suggest that production rates remain stable on the first and second day and only improved on the third. Table 4.7 shows that production rates remained low on the first day but managed to climb up a little on the second.

Results of the analysis

Table 4.9 shows that production rates were significantly different among the three different types of soil on the first day. However, only production rates for soil with low clay content were significantly different from soil with high and medium clay content on the second day. On the third day, all rates were not significantly different. These clearly indicate that production recovered significantly for soil with low clay content but the recovery on soil with high and medium clay content were hampered by the presence of moisture in the soil. Recovery became significant only when soil dried up.

Table 4.7: Production recovery for soils with different clay content

	Recovered Production Rates (%)								
	High Clay Content			Medium Clay Content			Low Clay Content		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
1st day	11	29	40	44	52	64	64	73	79
2nd day	22	49	79	52	69	100	74	85	100
3rd day	43	77	108	52	82	100	86	98	102

Table 4.8: P-values for soils with different clay content

	P-values (Between groups)		
	High Clay Content	**Medium Clay Content**	**Low Clay Content**
1st and 2nd day	0.124	0.090	0.049
2nd and 3rd day	0.100	0.369	0.031

Table 4.9: P-values between soils different clay content

	P-values (Between Groups)								
	1st Day			**2nd Day**			**3rd Day**		
	High	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
High	-	0.004	0.000	-	0.202	0.010	-	0.218	0.131
Medium	0.004	-	0.005	0.202	-	0.111	0.218	-	0.746
Low	0.000	0.005	-	0.010	0.111	-	0.131	0.746	-

The analyses illustrate the importance of incorporating difference of clay content in soil into production rates estimation as the effect on production due to rain on soil with high clay content is significant. For example, using mean values in Table 4.11, an average loss of 48.3% is expected due to rain on soil with high clay content, 32.2% on soil with medium clay content, and 14.7% on soil with low clay content. Assuming an average production rate of 200 lf/crew day, total productivity loss on high clay content soil is 290 lf, 194 lf for medium clay content soil, and 88 lf for low clay content soil. These results suggest that a one and a half day delay can be expected on high clay content soil, one day for medium content and less than half a day on low clay content.

The analysis confirms that clay content in soil is only a driver of production rate when there is moisture. Thus, in areas with high chance of rain, production rates should be adjusted accordingly.

4.6.2 Box Plots for Different Clay Content

Using Box Plots, recovered production rates in decimal terms, are plotted in Figures 4.20 to 4.23. The gaps between recovered production rates between different clay content in soil become increasingly small between first and fourth days after production resumes. Soil becomes drier as time increases. Observations, inputs from contractors and TxDOT personnel, and data show that wet soil is more difficult to work on and thus leads to lower productivity. Presence of high clay content in soil further reduces productivity. As seen in Figures 4.20 to 4.23, productivity in drier soil with high clay content is relatively similar to soil with lower clay content.

Figure 4.23 shows that most production recovers on the fourth day and p-values between three types of soil show insignificant difference (0.76). This illustrates that impact of moisture in clayish soil drags on for up to three days. Therefore, it is only useful to analyze recovered production rates for first three days after production resumes.

Figure 4.20: Recovered production on first day

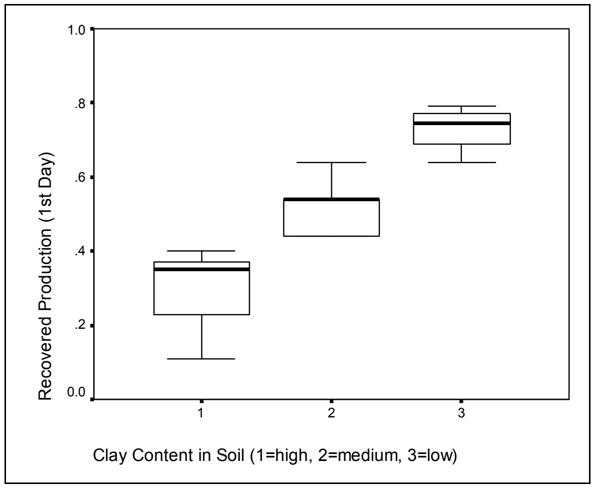


Figure 4.21: Recovered production on second day

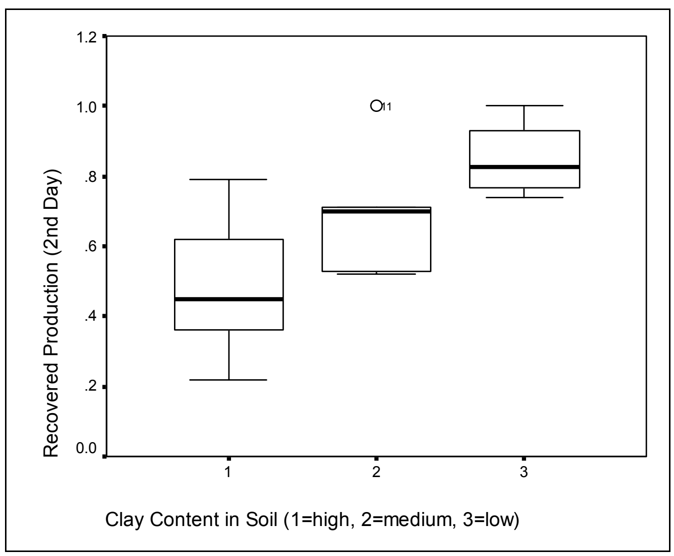


Figure 4.22: Recovered production on third day

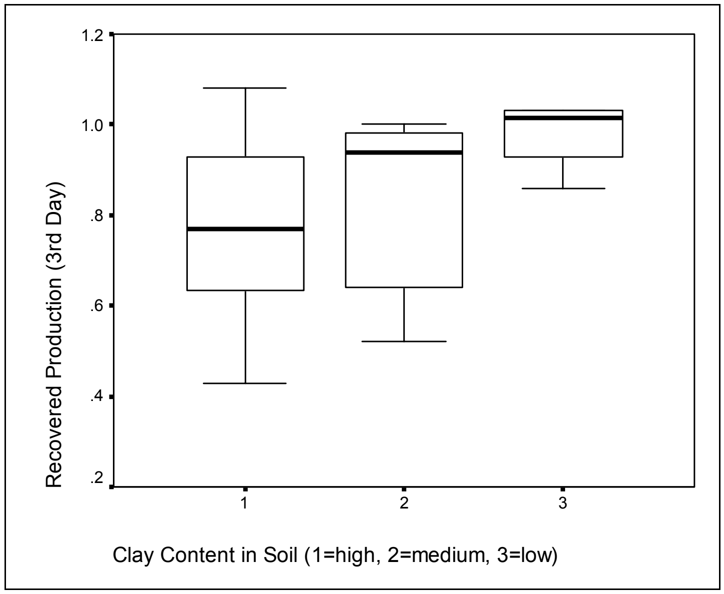


Figure 4.23: Recovered production on fourth day

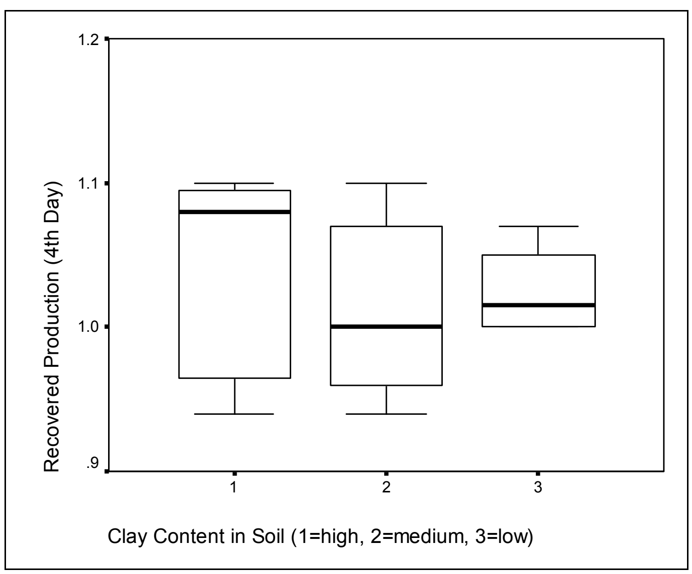
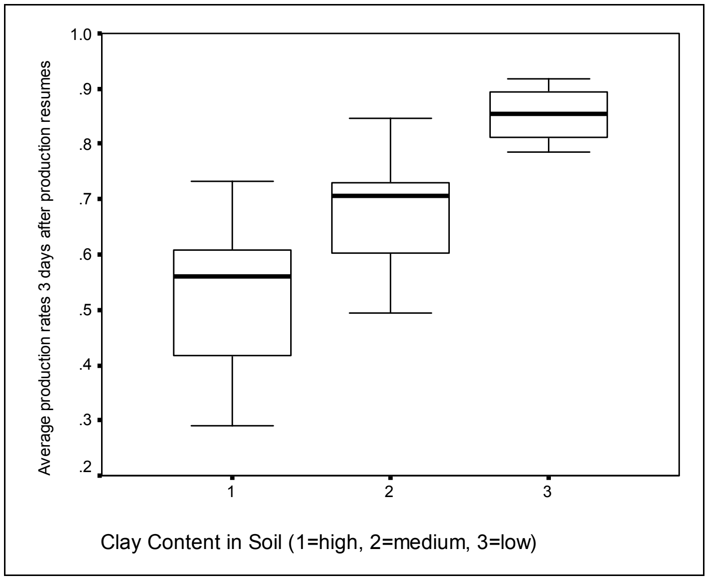


Figure 4.24: Average recovered production for first three days



Instead of developing as individual model for daily recovery, it is far more efficient to work from the means and averages of the three recovery days. On soil with high clay content, productivity losses range from 28% to 71% within the boundary of 3 inter-quartile range, and 40% to 59% within 1st and 3rd inter-quartile range with a mean of 52%. On soil with medium clay content, losses range from 15% to 52% within the boundary of 3 inter-quartile range, and 28% to 40% within one inter-quartile range with a mean of 30%. On soil with medium clay content, losses range from 8% to 21% within the boundary of 3 inter-quartile range, and 10% to 18% within one inter-quartile range with a mean of 15%. The following table summarized value ranges.

Table 4.10: Ranges of production losses over three recovery days

Clay Content	Mean	Inter-quartile Range	3 Inter-quartile Range
High	52%	40% - 59%	28% - 71%
Medium	30%	28% - 40%	15%- 52%
Low	15%	10% - 18%	8% - 21 %

Designers can select a value from the mean, inter-quartile range, and 3 inter-quartile range to adjust their calculated Reinforced concrete pipes and Precast box culverts production rates using formulae from Sections 4.4 and 4.5. For example, in regions with high likelihood of rain on soil with high clay content, designers may estimate a production loss of 59%. Then, they can estimate the total number of days rain will affect production and multiple 59% to the estimated production rates. Both "normal" and "disrupted" production rates have to be added together to derive a new rate. The proportion of the "normal" and "disrupted" production rates to be included in the new rate depends the estimated number of times rain will affect production and will not affect production.

CHAPTER 5 : HIGHWAY PRODUCTION RATE INFORMATION SYSTEM

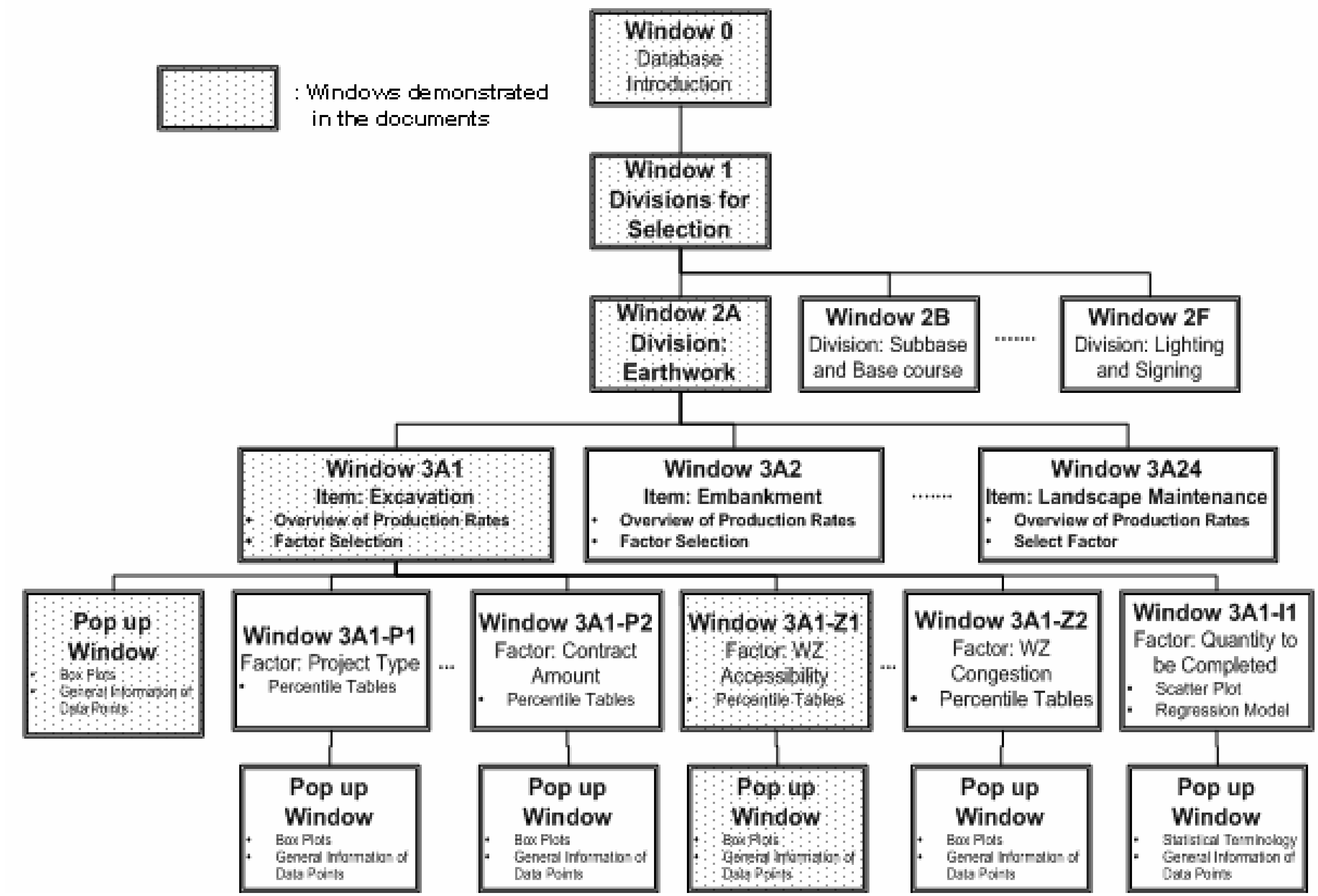
The development of an information system was the final objective of this research. The information system serves as a tool that organizes and disseminates key production rate findings from this research. The system is called the Highway Production Rate Information System (HyPRIS). To ensure user-friendliness of the system, HyPRIS was developed with Microsoft Visual Basic and saved as an Microsoft Excel file.

5.1 INFORMATION IDENTIFICATION FOR HYPRIS

The key findings from the research were presented in four different information elements. The first information element involves information that would be used by the Texas Department of Transportation (TxDOT) to estimate production rates. Such information includes production rate decile tables, regression plots, results of the regression analyses, and box plots. The second information element contains a glossary of terms that describes some statistical terms adopted in the research. The third information element consists of descriptions of individual assessed work items. The fourth information element includes useful related information from the Contract Time Determination System (CTDS).

The first three information elements are presented according to work item. whereas the fourth element is presented in a separate window that is not linked to any work items.

Figure 5.1 HyPRIS Structure



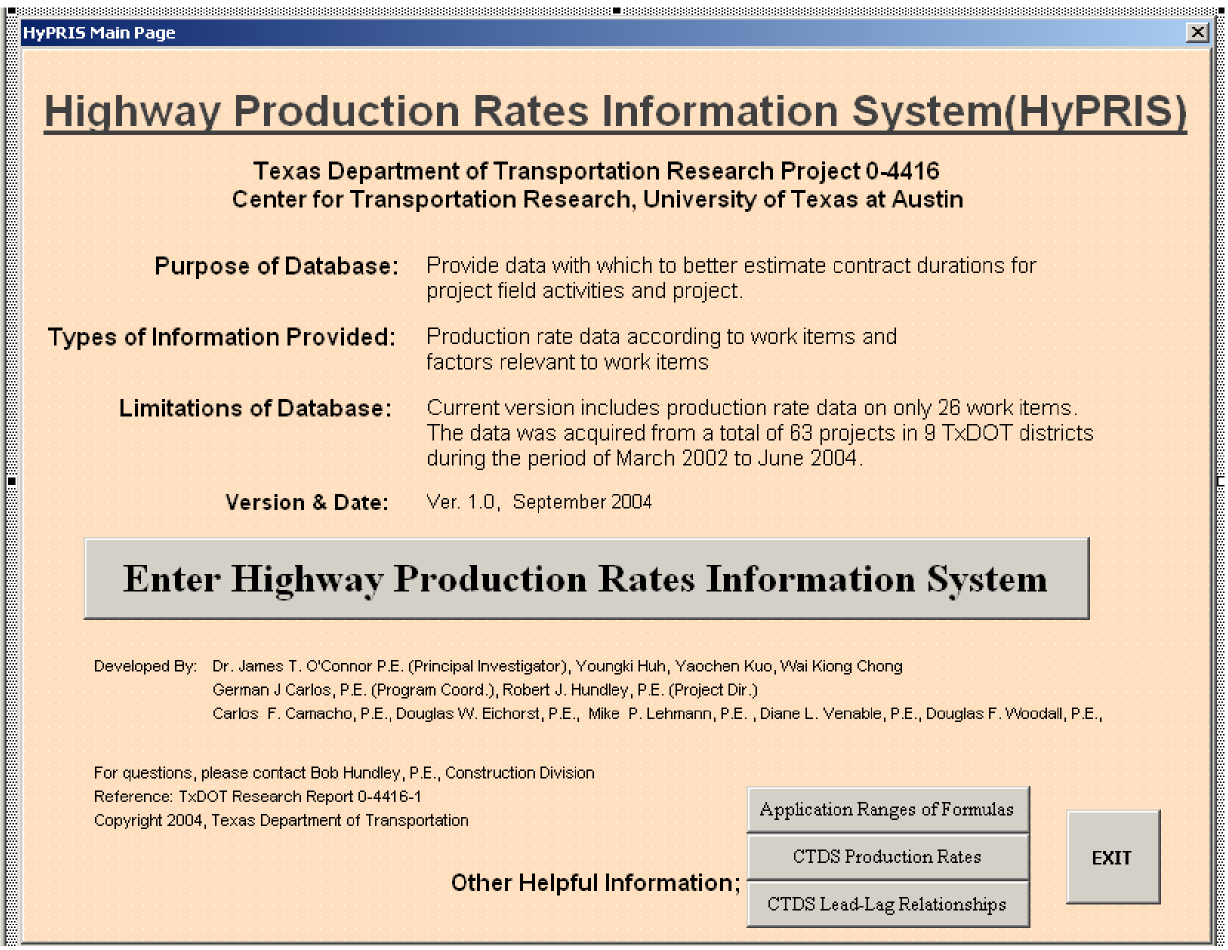
The system is structured in four main levels, as shown in Figure 5.1. The first level generally groups the work items into divisions so that users can easily search for the work items that they are looking for. The second level separates the work items into the work item numbers that are prescribed in the TxDOT Specifications Handbook (2004). Users can immediately identify work item numbers and descriptions at this level. The third level contains production rate information that users are looking for. This information is presented in the following manner: (1) overall information for the work item, (2) information particular to a significant driver of the work item, and (3) information particular to describing the work item. The following sections will give more detailed description of the entire system.

5.2 HyPRIS Framework

Figure 6.2 shows the HyPRIS main page window that is presented once the link to the file is executed. This window frame explains the details of the research, provides information on what to expect, and links the user to the information elements in the database. There are five buttons on this window. The largest button links the first window to the three information elements that are grouped by different work items. Three buttons at the bottom provide links to useful CTDS information and guidelines about the usage of formulas in the system. The Exit button appears in most of the windows. This is to provide the users with an option to exit if they would like to stop using the system.

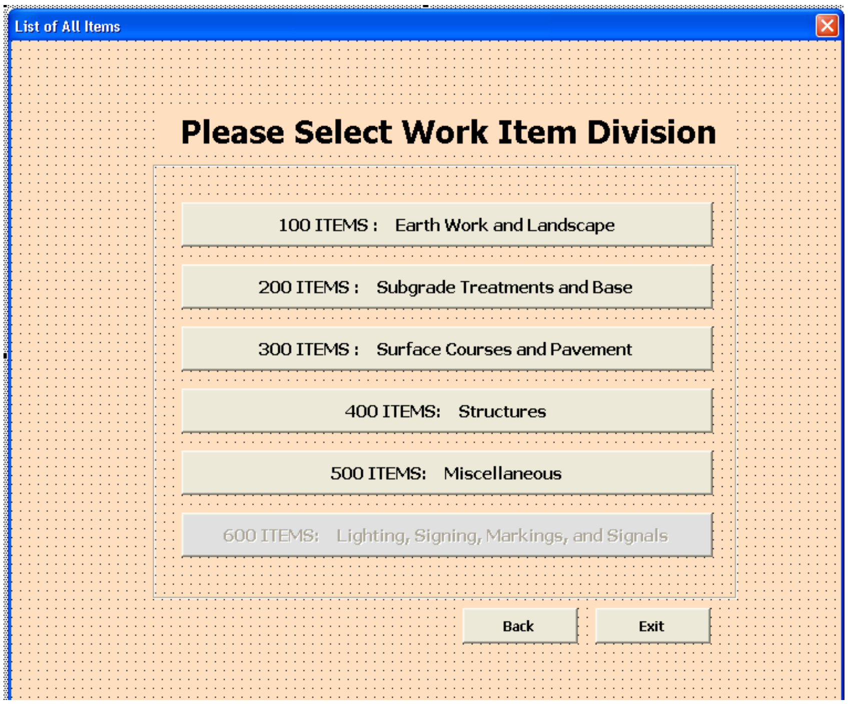
The fourth information element contains CTDS lead–lag relationships and production rates. Because the research did not address lead–lag relationships between different work items and does not have the production rates of the other sixteen work items used in the CTDS, this information element provides temporary help for the users until this information is updated.

Figure 5.2 HyPRIS Main Frame



Once users proceed to production rates, five work item divisions appear on a window, as shown in Figure 5.3. These windows (Figures 5.2 and 5.3) are first-level windows.

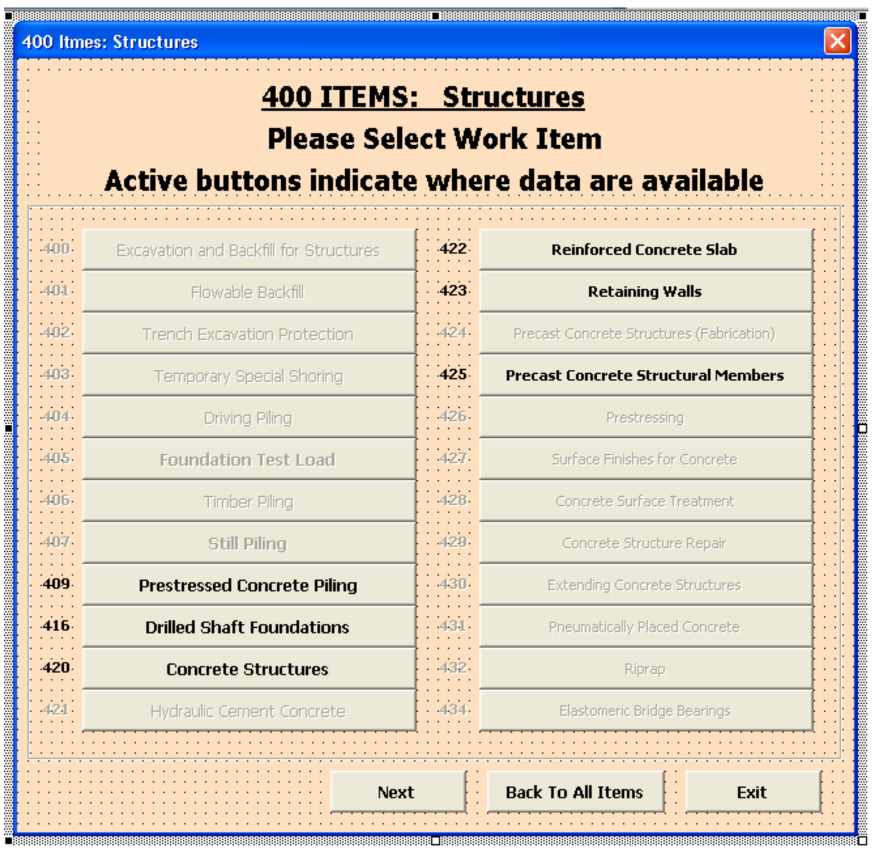
Figure 5.3: Work Item Division, First Window



The users can select from the work item divisions in this window to gain access to detailed work items. Each work item division contains all the work items under each division. For example, Work Item Number 464 (Reinforced Concrete Pipes) is a subitem in the "400 Items: Structures" division.

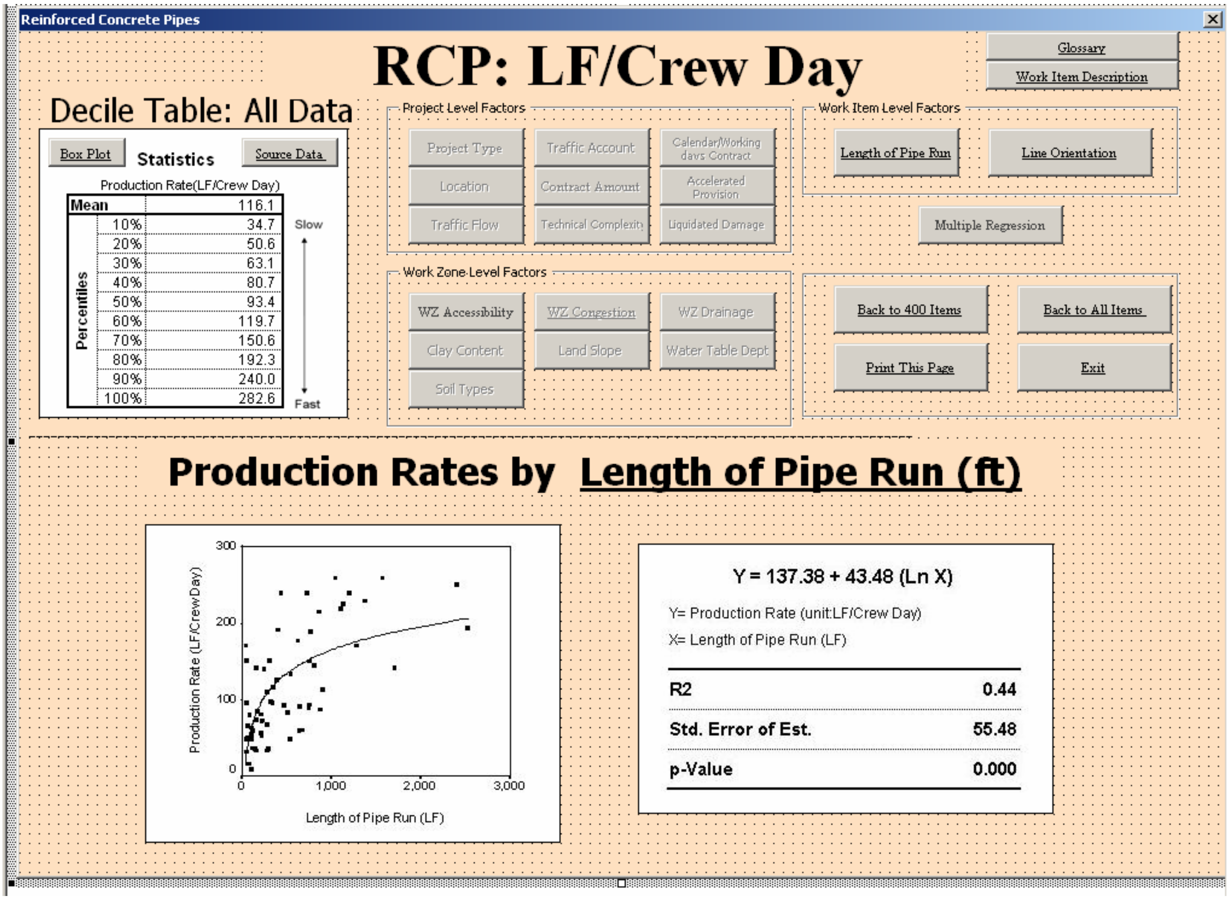
Once the users enter a Division series, they will find one or more second-level windows. All work items are arranged according to work item number, and brief titles of work items are associated with each work item number. An example is shown in Figure 5.4.

Figure 5.4: Work Item Numbers Window



Once user identifies the work item they want, a click on the work items button will lead them to a third-level window, as shown in Figure 5.5.

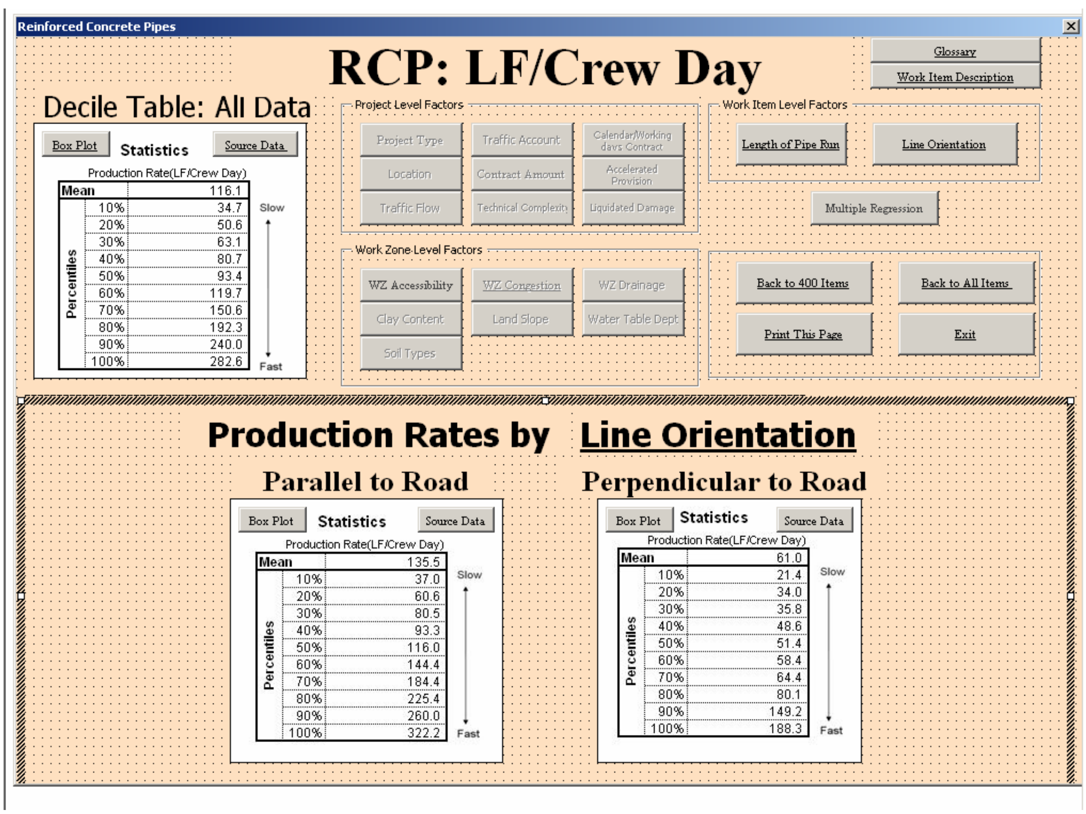
Figure 5.5: Work Item (RCP) Main Frame



The three information elements, discussed earlier in this chapter, are documented at this window level. The decile table on the upper left-hand corner shows the distribution range of the observed production rates. Decile tables are based on all relevant data points, and tables were developed for all significant work item drivers. The significant drivers appear as active buttons with bolded wording in the subframes of Work Item Level Factors, Work Zone Level Factors, and Project Level Factors. A pop-up frame appears if an active button is clicked. For example, a scatterplot and formula appear when the button Length of Pipe Run is clicked. This is another third-level window. Scatterplots alongside a regression formula are used to represent the relationship between the significant driver and the production rate.

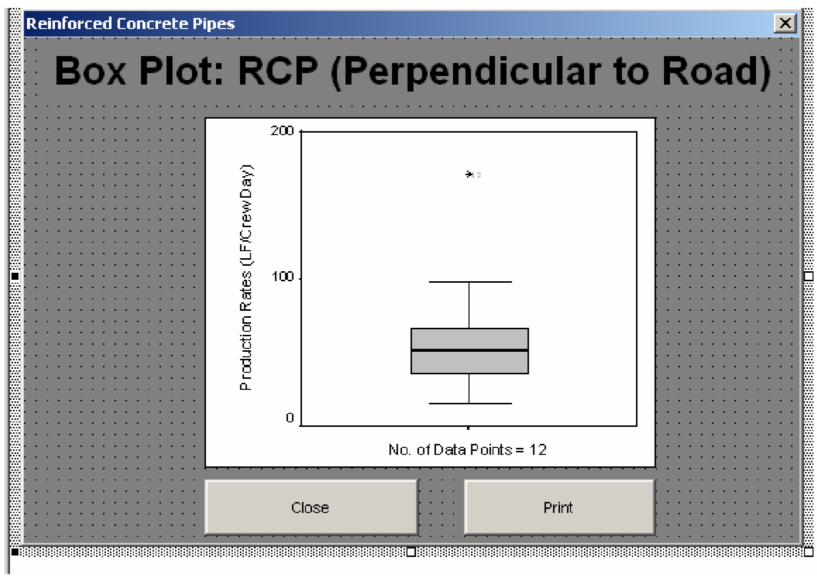
A click on the Line Orientation button pops up the frame for Line orientation findings, as shown in Figure 5.6. Because Line orientation is a categorical driver, decile tables are used to represent the relationship between the driver and production rate. This is another third-level window.

Figure 5.6: Frame for Line Orientation



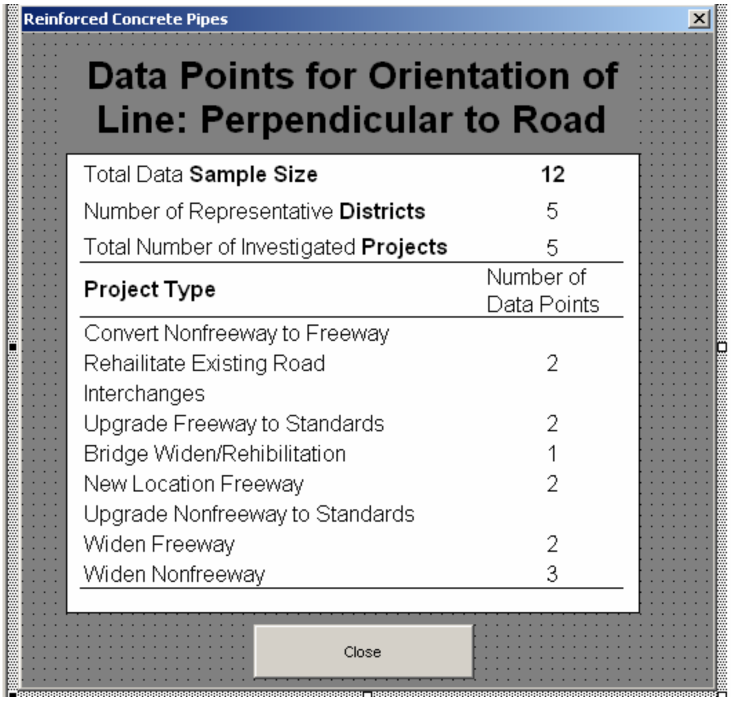
The Box Plot and Source Data buttons on the top left- and right-hand sides of the decile tables, shown in Figure 6.6, provide links to other essential information. These windows can be seen in Figures 6.7 and 6.8. This information provides helpful guidance to users. The Box Plot button links to the box plot for the data, and the Source Data button links to the types of projects from which the data was gathered.

Figure 5.7: Box Plot for RCP



The Source Data screen shows the total number of data points, the total number of districts and the number of projects the data were collected from, and the types of projects. Such information may help users in deciding whether the data are relevant to their particular estimations.

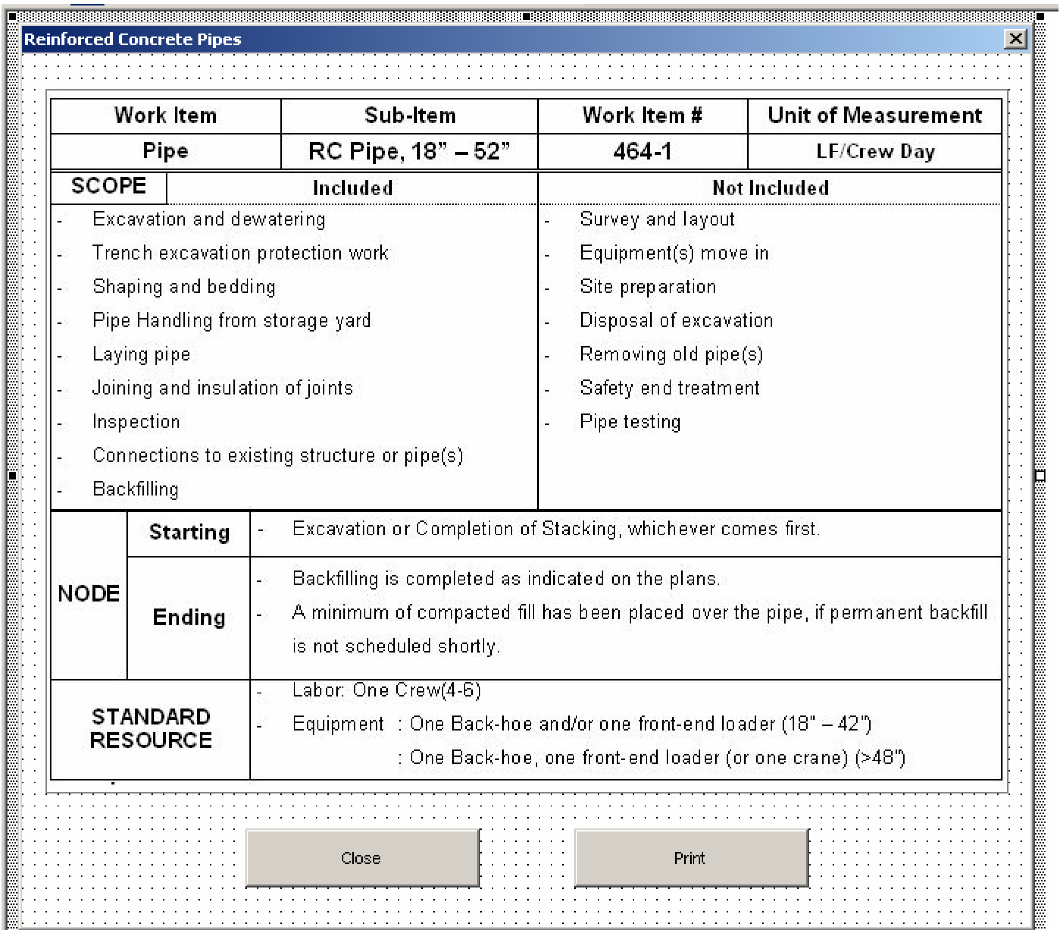
Figure 5.8: Source Data for RCP



Total Data **Sample Size**	**12**
Number of Representative **Districts**	5
Total Number of Investigated **Projects**	5
Project Type	Number of Data Points
Convert Nonfreeway to Freeway	
Rehailitate Existing Road	2
Interchanges	
Upgrade Freeway to Standards	2
Bridge Widen/Rehibilitation	1
New Location Freeway	2
Upgrade Nonfreeway to Standards	
Widen Freeway	2
Widen Nonfreeway	3

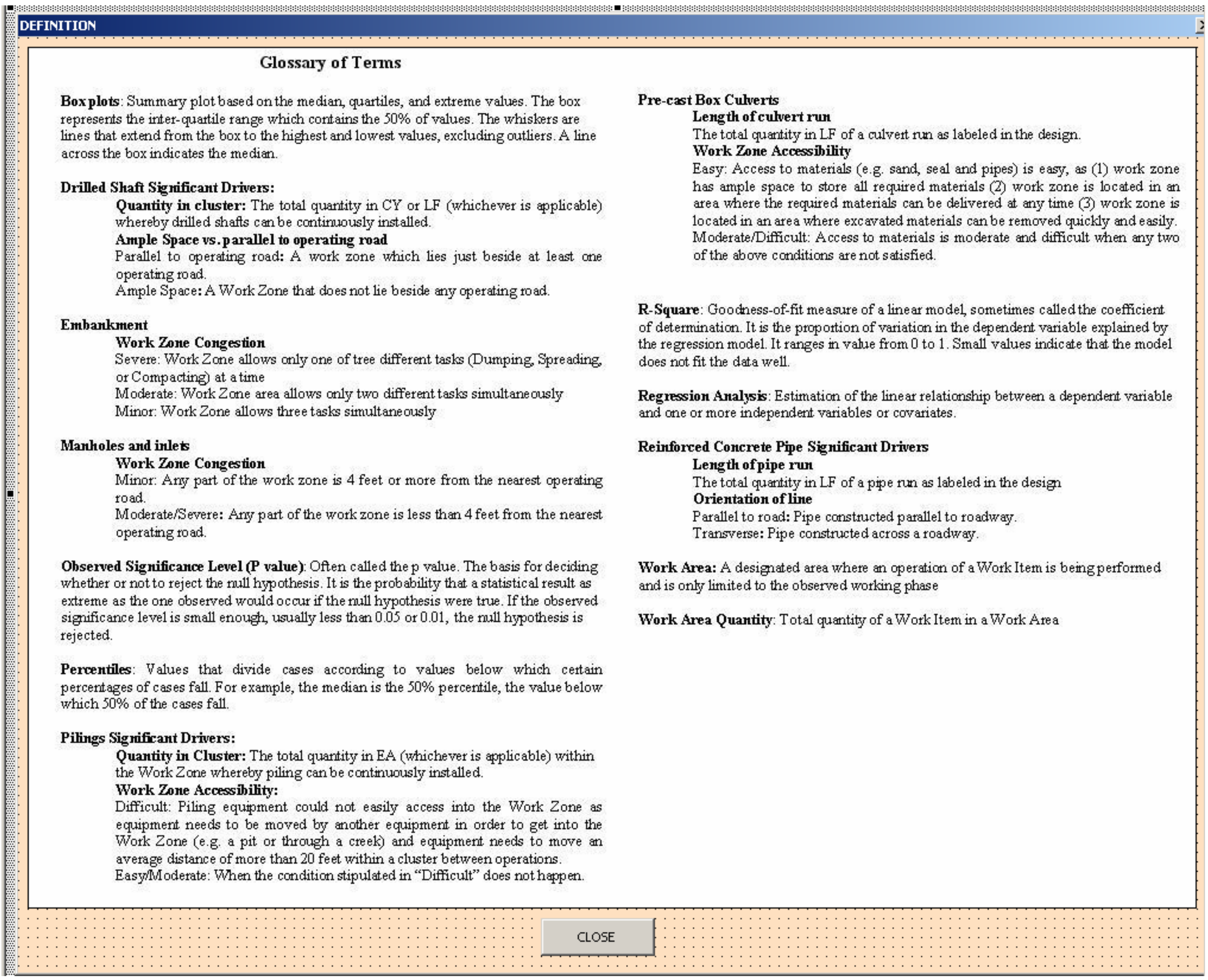
Two buttons on the top right hand corner — namely, Glossary and Work Item Description, as shown in Figure 5.6 — link to additional useful information for estimators.

Figure 5.9: Window for Work Item Description



The Work Item Description window characterizes the scope of work included in the measurement of the production rate for the work item. It also states the standard resource generally applied in achieving such production rates.

Figure 5.10: Glossary Table



DEFINITION

Glossary of Terms

Box plots: Summary plot based on the median, quartiles, and extreme values. The box represents the inter-quartile range which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. A line across the box indicates the median.

Drilled Shaft Significant Drivers:

Quantity in cluster: The total quantity in CY or LF (whichever is applicable) whereby drilled shafts can be continuously installed.

Ample Space vs. parallel to operating road

Parallel to operating road: A work zone which lies just beside at least one operating road.

Ample Space: A Work Zone that does not lie beside any operating road.

Embankment

Work Zone Congestion

Severe: Work Zone allows only one of tree different tasks (Dumping, Spreading, or Compacting) at a time

Moderate: Work Zone area allows only two different tasks simultaneously

Minor: Work Zone allows three tasks simultaneously

Manholes and inlets

Work Zone Congestion

Minor: Any part of the work zone is 4 feet or more from the nearest operating road.

Moderate/Severe: Any part of the work zone is less than 4 feet from the nearest operating road.

Observed Significance Level (P value): Often called the p value. The basis for deciding whether or not to reject the null hypothesis. It is the probability that a statistical result as extreme as the one observed would occur if the null hypothesis were true. If the observed significance level is small enough, usually less than 0.05 or 0.01, the null hypothesis is rejected.

Percentiles: Values that divide cases according to values below which certain percentages of cases fall. For example, the median is the 50% percentile, the value below which 50% of the cases fall.

Pilings Significant Drivers:

Quantity in Cluster: The total quantity in EA (whichever is applicable) within the Work Zone whereby piling can be continuously installed.

Work Zone Accessibility:

Difficult: Piling equipment could not easily access into the Work Zone as equipment needs to be moved by another equipment in order to get into the Work Zone (e.g. a pit or through a creek) and equipment needs to move an average distance of more than 20 feet within a cluster between operations.

Easy/Moderate: When the condition stipulated in "Difficult" does not happen.

Pre-cast Box Culverts

Length of culvert run

The total quantity in LF of a culvert run as labeled in the design.

Work Zone Accessibility

Easy: Access to materials (e.g. sand, seal and pipes) is easy, as (1) work zone has ample space to store all required materials (2) work zone is located in an area where the required materials can be delivered at any time (3) work zone is located in an area where excavated materials can be removed quickly and easily.

Moderate/Difficult: Access to materials is moderate and difficult when any two of the above conditions are not satisfied.

R-Square: Goodness-of-fit measure of a linear model, sometimes called the coefficient of determination. It is the proportion of variation in the dependent variable explained by the regression model. It ranges in value from 0 to 1. Small values indicate that the model does not fit the data well.

Regression Analysis: Estimation of the linear relationship between a dependent variable and one or more independent variables or covariates.

Reinforced Concrete Pipe Significant Drivers

Length of pipe run

The total quantity in LF of a pipe run as labeled in the design

Orientation of line

Parallel to road: Pipe constructed parallel to roadway.

Transverse: Pipe constructed across a roadway.

Work Area: A designated area where an operation of a Work Item is being performed and is only limited to the observed working phase

Work Area Quantity: Total quantity of a Work Item in a Work Area

CLOSE

The glossary provides useful information on statistical terminology and other work item and factor terms that are perhaps applied in a unique manner in this research.

5.3 HyPRIS Design — Support Functions

HyPRIS was designed to enhance users' convenience. A Print button is inserted in all production rate windows so that users can print a copy of the window before proceeding to another window. This ensures that they do not have to go back and forth to search for other information. However, users are *required to set the printing to landscape orientation*.

The Close button on the windows allows users to close the window at any time. Users are able to navigate around the system using the support buttons (e.g., Back to 400 Items, Back to All Items, and Exit, as shown in Figure 5.4).

HyPRIS Design — Maintaining and Updating the System

To reduce the complexity of updating and maintaining the system, HyPRIS makes use of jpeg files for all information like scatterplots, decile tables, tables, box plots, and data points information sources.

Links Between Windows

Buttons are used to provide linkages to any of the windows and frames. The required computing language can be found in the MS Visual Basic manual.

Supporting Information for the Estimators

Information such as scatterplots, decile tables, box plots, data sources, glossary, regression plots, and work item descriptions are presented in jpeg files. System administrators are encouraged to read manual in Appendix J for details on the size of each file while users should refer to Appendix I for better understanding the function of HyPRIS.

System administrators should note that different representations of information in the system were designed using different media. The media/software types are listed in the following table.

Table 5.1: Media and Software used in HyPRIS

Information	**Media/Software**
Screens and buttons	MS Visual Basic
Scatterplots/box plots	SPSS version 11.0 and converted to jpeg format
Decile tables/source data	MS Excel Files converted to jpeg format
CTDS/glossary/work item description	Jpeg format

Statistical Software

Researcher used SPSS for all related statistical analysis. SPSS will be needed for any future expansion of HyPRIS.

CHAPTER 6 : CONCLUSIONS, RECOMMENDATIONS AND CONTRIBUTIONS

6.1 CONCLUSIONS

Chapters 1 to 5 have fulfilled the four objectives of this research. The first objective was to collect accurate information on production rates and productivity drivers such that this information could be used to develop a production rate information system. Field production rates were identified as the most accurate data source and data were collected from foremen's diaries, site records, and project managers' records on weekly site visits to 65 highway projects across Texas. Data collection tools were developed to support data collection process. The tools are a series of systematic recording systems to register production drivers, daily production rates, and daily events occurring on sites everyday. Construction drawings and specifications were used to verify accuracy of inputs from site personnel. Collected data were then consolidated using Microsoft Access. Production rates and drivers were associated with each data point. A production rate was calculated for each data point and each data point has its own associated drivers.

The second objective required the selection and usage of appropriate statistical methods to hypothesize and test relationships between production rates and drivers. Box-plots, linear and non-linear regression, and multivariate regression were used to determine relationships between production rates and drivers and to develop models for selected work items. R-square values and ANOVA test were used to examine such relationships and to determine whether it was useful to pursue further analysis. Drivers that were identified for further analyses are labeled as “significant drivers”. These drivers were then quantified in order to fulfill the third objective.

The third objective was to quantify associated relationships using statistical modeling. This was fulfilled by using linear, non-linear, and multivariate regression modeling to develop models for significant numeric drivers and box-plots are used to develop for significant categorical drivers.

The final objective of this research was to develop a production rate information system to assist design engineers in the process of time estimation. The system is called the Highway Production Rates Information System (HyPRIS) and was developed using Visual Basic. Two other graduate student assisted significantly on this effort.

6.2 RECOMMENDATIONS

There are several recommendations for future studies:

- Additional work items should be included in HyPRIS:

  To enhance the usefulness of HyPRIS, more work items should be included into the system. Similar research process can be used to collect new data, analyze production rates and drivers, and develop models for new work items.

- Lead and lag relationships between different work items should be included in HyPRIS:

  Relationships between different work items need to be established in order to develop a complete project schedule. HyPRIS can become a more useful system if it can incorporate lead and lag relationships.

- Establishing a TxDOT database system to support future computation of production rates:

  HyPRIS is only useful if collected information is accurate. Field data is considered a reliable source of information but it is extremely cumbersome to collect. Regular site visits found that many sites kept extremely good records of their field production data. Many of these were simply left on the record books and computers. Many prefer not to use them as records were too massive and difficult to extract. To better exploit these data, there is a need to design a database that can document, extract, and analyze information at the same time. With so much information available, there are needs for TxDOT to establish such database.

- Implementation and maintenance of HyPRIS:

  HyPRIS's success depends on three key factors. First, it should be used by all TxDOT engineers involved in estimating construction duration. High usage is necessary in order to establish the legacy of the system. Also, if this occurs, chances of feedback will be higher and improvement can be done regularly to improve the system. Second, frequent system updating should be carried out. HyPRIS will become obsolete if it is not updated regularly. Third, TxDOT should assign maintenance team to take care of HyPRIS. Feedback from users should be properly addressed and minor updates should be done regularly to ensure HyPRIS functions properly all the time. The key words are "maintain", "update", and "upgrade".

6.3 RESEARCH CONTRIBUTIONS

There are three major contributions from this research. These contributions include the establishment of a data collection framework for the purpose of production rate estimation at the design stage, data analysis and modeling of production rates and productivity factors, and improving efficiency of data extraction for production rate estimation via the HyPRIS tool. Future researchers can rely on the data collection framework and the data analysis examples to develop similar production rate information for other work items.

In addition, weather impact on observed production rates has been removed. The treatment of weather for CTDS production rates is uncertain, as the issue is not documented. Future research should appropriately adjust such impact on production rates to ensure the accuracy of the estimation process.

APPENDIX A: QUESTIONNAIRE FOR SELECTING WORK ITEM FOR THE STUDY

Questionnaire for Selecting Work Items for the Study

Name : ________________

District : ________________ Position : ____________________

Site/Office Address :____

Phone Number : ________________ E-mail Address : ____________________

Please check as you think it is most appropriate

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Initial traffic control	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Detour	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
ROW Preparations								
Clear & Grub	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove old structure(small)	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove old pavement	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove old curb & gutter	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove old sidewalks	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove old drainage/utility structures	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Major structure demolition	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
Excavation/embankment								
Earth excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Rock excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Embankment	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Drainage structures/storm sewers								
Pipe	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Box culverts	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Inlets & Manholes	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge Structures								
Erect temporary bridge	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge demolition	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Cofferdams	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Piling	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Footings	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Columns, caps & bents	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Wingwalls	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	**Definitely Track?**	**Degree of Variability in Crew Productivity**			**How often On or Near Critical Path**			
	Yea/**N**o	**L**ow	**M**oderate	**H**igh	**Rarely**	**Sometimes**	**Often**	**Usually**
Beams (erection only)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge deck (total depth)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge curb/walk	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge handrail	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove temporary bridge	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Retaining walls	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Base Preparations								
Lime stabilization	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Flexible base material	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Cement treated base material	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
New curb & gutter	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Hot mix asphalt base	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Concrete paving	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Hot mix asphalt surface	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent signing & traffic signals								
Small signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Overhead signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Major traffic signals	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Seeding & Landscape	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent pavement markings	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Final clean up	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Others								
______________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
______________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
______________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually

Your Comment (*We appreciate your comment*)

Are you interested in continued participation in this study? Yes No

Thank You.

APPENDIX B : RESULTS OF THE SURVEY FOR SELECTING WORK ITEMS TO BE TRACKED

Results of the Survey for Selectiing Work Items to be tracked

Work Items	Definitely Track? - 'Yes' Response													Total of 'Yes'
	Bob. H.	Carlos C.	Doug W.	Dan D.	Mike L.	Harry P.	Mario R.G.	David H.	Pat W.	Mike B.	Duane S.	Tom N.	Mike C.	
Initial traffic control					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Detour					Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	8
ROW Preparations														
Clear & Grub					Yes		Yes	Yes	Yes	Yes			Yes	6
Remove old structure(small)							Yes	Yes	Yes			Yes		4
Remove old pavement					Yes		Yes	Yes	Yes		Yes	Yes		6
Remove old curb & gutter							Yes	Yes	Yes					3
Remove old sidewalks							Yes	Yes	Yes					3
Remove old drainage/utility structures		Yes			Yes		Yes	Yes	Yes					5
Major structure demolition		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Excavation/embankment														
***Earth excavation**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Rock excavation	Yes				Yes		Yes	Yes		Yes			Yes	6
***Embankment**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Drainage structures/storm sewers														
Pipe	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Box culverts	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Inlets & Manholes	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Bridge Structures														
Erect temporary bridge		Yes					Yes		Yes					3
Bridge demolition		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Cofferdams					Yes		Yes		Yes		Yes			4
Piling		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Footings					Yes		Yes	Yes	Yes	Yes	Yes		Yes	7
Columns, caps & bents	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Wingwalls		Yes			Yes			Yes	Yes	Yes	Yes		Yes	7
Beams (erection only)		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Bridge deck (total depth)	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Bridge rail	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
Bridge curb/walk							Yes	Yes	Yes					3
Bridge handrail		Yes						Yes						2
Remove temporary bridge		Yes							Yes	Yes	Yes			4
Retaining walls	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Base Preparations														
***Lime stabilization**	Yes				Yes		Yes		Yes	Yes	Yes	Yes		7
***Flexible base material**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Cement treated base material**	Yes	Yes			Yes		Yes		Yes	Yes	Yes			7
New curb & gutter	Yes				Yes		Yes	Yes	Yes		Yes		Yes	7
***Hot mix asphalt base**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Concrete paving**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
***Hot mix asphalt surface**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Permanent signing & traffic signals														
Small signs					Yes			Yes	Yes					3
Overhead signs		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Major traffic signals					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Seeding & Landscape					Yes			Yes	Yes					3
Permanent pavement markings		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Final clean up		Yes			Yes			Yes	Yes		Yes		Yes	6
Total of 'Yes'	17	21	0	0	35	0	36	37	40	25	31	25	22	
Others		Traffic Switches, Temporary Striping, CTB Move & Reset			Utility Installation /adjustment				Drill Shaft/ Surface Treatment	Planning Hot Mix Pav't	Drill Shaft			

APPENDIX C: PRODUCTION RATE TRACKING (PROJECT LEVEL)

Production Rate Tracking : Project level

CCSJ # :

Highway # :

Project ID:

Project Length :

Station Range :

District :

City/County :

Prime Contractor:

Contract Amount : $ Million

% of Project Completion : %

Project(Construction) Period : --- (Calandar/Working days)

Work Items to be tracked:

Item #	Work Item	Unit	Approx. Total Quantity	Scheduled Start Date	Scheduled End Date	Sub- Contracted?	Comments
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	
						Yes □ No	

Please, fill out next page.

Project-Level Data Collection Tool (Cont’d)

Project Level Variables Evaluation

Project CCSJ:

Variable		Unit	Optional Values				
Project Type			□ Seal Coat	□ Overlay	□ Rehabilitate Existing Road	□ Convert Non-Freeway to Freeway	
			□ Widen Freeway	□ Widen Non-Freeway	□ New Location Freeway	□ New Location Non-Freeway	
			□ Interchanges	□ Bridge Widening/ Rehabilitation	□ Bridge Replacement/ New Bridge	□ Upgrade Freeway to Standards	□ Upgrade Non-Freeway to Standards
Location			□ Rural	□ Urban	□ Metro		
Traffic Flow			□ Rarely congested	□ Only rush hours congested	□ Most hours congested		
Traffic Count (ADT)		Veh./ Day	□ < 5 K	□ 5 K ~ 20 K	□ > 20 K		
Weather	Annual Precipitation	/Year	□ < 15”	□ 15”~40”	□ > 40”		
	Winter Season Length		□ Costal	□ Central & South Texas	□ North Texas	□ Panhandle & West Texas	
% of Construction Completion at 1st Data Collection Date		%	□ 0-30	□ 30-70	□ 70-100		
Size : Construction Contract Amount		$	□ <5M	□ 5M ~ 20 M	□ 20M ~ 50 M	□ >50M	
Technical Complexity			□ Simple	□ Moderate	□ Complex		
Contract	Contract Day		□ Calendar Day	□ Working Day			
	Accelerated Constrcution Provision		□ None	□ Incentive Using Contract Administrative Cost	□ Milestones with Incentives/ Disincentives		
			□ Substantial Completion I/D	□ Lane Rental Disincentive	□ A+B Provisions		
	Liquidated damages	$/Day	□ < 300	□ 300~3K	□ 3K~6K	□ 6K~12K	□ > 12K
Soil types			□ Loose	□ Stiff	□ Rocky		
Local site Drainage Effectiveness	Clay Content (Plastic Soils)		□ Low	□ Moderate	□ High		
	Land Slope		□ Flat	□ Moderate	□ Steep		
	Water Table Depth below Grade		□ < 4'	□ 4' ~ 10'	□ > 10'		
Scheduling Technique Used			□ Bar Chart	□ CPM (Not Resource-loaded)		□ CPM (Resource-loaded)	
Work Schedule	Days per Week (typical)	Day/Week	□ 4	□ 5	□ 6	□ 7	
	Hours per Day(typical)	Hours/Day	□ 8	□ 10	□ 12	□ 2 Shifts	
Contract Admin. System			□ C.I.S.	□ Site Mgmt.			
CMS (Contractor Management Skill)			□ Good	□ Average	□ Poor		

APPENDIX D: PRODUCTION RATE TRACKING: WORK ZONE LEVEL

Production Rate Tracking: Work Zone Level

Work Zone & Work Item Assessed **Recorder : ______________**

Project ID: ______________________ Work Item (No.): ___________________________

District : ______________

Work Zone Description/Sketch:

Description:	Sketch
Description: ________________________________ ________________________________ ________________________________	Sketch
Typical Workday Start Time: ___________	
Typical Workday Stop Time: ___________	
Is observed work item on critical path? ☐ Yes ☐ No	
Workers are from: ☐ Union ☐ Non-Union	
How much quantity included in a work item operation cycle: ____________________ (☐ Not Affected)	▪ *No. indicates the No. of Traffic lines* ▪ *Double line indicates that WZ is not affected by its side of traffic.*

Work Zone Level Variables Evaluation

Variable		Characterization	Comment
1	WZ Accessibility	Difficult Moderate Easy Not Applicable	
2	WZ Construction Congestion	Severe Moderate Minor Not Applicable	
3	Work Zone Site Drainage Effectiveness	Easily Flooded Moderate Quickly Drains Not Applicable	
3.1	Clay Content in Soil	High Moderate Low Not Applicable	
3.2	Land Slope	Steep Moderate Flat Not Applicable	
3.3	Water Table Depth Below Grade	<4’ 4’~10’ >10’ Not Applicable	

Data Analysis Status

Data Point ID:______________________	*☐ Check if data Collection completed* *☐ Check if data Input completed*

Production Rate Tracking: Work Zone Level (Cont'd)

Work Item Sheet to be Inserted

APPENDIX E : PRODUCTION RATE TRACKING: WORK ITEM LEVEL

Production Rate Tracking: Work Item Level

Observation Record

First Date of the Observed Operation		
Overall **Work Item Completion** in the project at 1st Data Collection Date	☐ 0-20% ☐ 20-80% ☐ 80-100%	☐ 0-100% (Observed Whole Process)

Completion Status: Fully Labeled Sketch, Description & Note

Please take note the 'Quantity of Con'c Placed' and/ or quantities of other alternative units, whenever it is possible.

Quantity Completed		Unit	

Production Rate Tracking: Work Item Level (Cont'd)

Observation Record

Resource Efforts for Work Item		
Crew		
Crew Type	Average Skill Level	Typical Crew Size
	Novice Typical Experienced	
	Novice Typical Experienced	
	Novice Typical Experienced	
	Novice Typical Experienced	
Equipment		
Equipment Piece	Equipment Size	Typical Number in Operation

APPENDIX F: TRACKING CALENDAR

Tracking Calendar (Work Item Level)

Year:________

Sunday		Monday		Tuesday		Wednesday		Thursday		Friday		Saturday	
/	**I** **II** **III** **VI**	/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	

I: Observation #, **II**: X, ○ or ⊖, **III**: Indication , **VI**: Comment No.

Total Working Days: ____________________

Indication

Ⓣ **- #**: **T**his Observation #	Ⓗ: **H**oliday or Day Off
Ⓦ: **W**eather day (< 2 Hrs of work)	Ⓢ: Work Day With **S**ome Weather Effect
Ⓝ: U**N**workable Soil Condition	Ⓘ: **I**ncomplete Crew
Ⓔ: **E**quipment Downtime/not Available	Ⓜ: **M**aterial Unavailable
Ⓤ: **U**tility Conflicts	Ⓕ: Un**F**oreseen Condition
Ⓒ: **C**onstruction Accident	Ⓐ: Traffic **A**ccident
Ⓞ: **O**vertime	Ⓓ: Other **D**elay (specify in comments)

○ : Normal Working Day ⊖ : ½ Working Day X: Non Working Day

Comments:

①	
②	

Tracking Calendar (Work Item Level) (Cont'd)

Comments (Continued):	
③	
④	
⑤	
⑥	
⑦	
⑧	
⑨	
⑩	
⑪	
⑫	
⑬	
General Comment	

APPENDIX G: WORK ITEM SHEETS

WORK ITEM SHEETS

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	**RC Pipe, 18" – 42"**	**464-1**	**LF/Std. Res. Day**

SCOPE	**Included**	**Not Included**
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Pipe Handling from storage yard - Laying pipe - Joining and insulation of joints - Inspection - Connections to existing structure or pipe(s) - Backfilling	- Survey and layout - Equipment(s) move in - Site preparation - Disposal of excavation - Removing old pipe(s) - Safety end treatment - Pipe testing

Work Item Level PRODUCTIVITY FACTOR		**Diameter of Pipe (18", 21", 30", 36", 42"), (Note;________________________________)** **Connection to Existing Structure or Pipes (Yes, No), (Note;________________________)** **Approximate Trench Depth (Specify;____)** **Any Utility Conflict (None, Low, Average, High), (Note;___________________________)** **No. of Inlet & Manhole in the section (Specify;_________________________________)** **No. of Inlet & Manhole installed during observation period (Specify;________________)** **No. of Pipe line (Single, Double), (Note;____)**
		- Soil Type / Water Table Depth
NODE	**Starting**	- Excavation or Completion of Stacking, whichever comes first.
	Ending	Backfilling is completed as indicated on the plans. A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.
STANDARD RESOURCE		- Labor: One Crew(4-5) - Equipment: One Back-hoe
		Comment ; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

APPENDIX G. WORK ITEM SHEETS (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	**RC Pipe, 48" – 72"**	**464-2**	**LF/ Std. Res. Day**

SCOPE	Included	Not Included
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Pipe Handling from storage yard - Laying pipe - Joining and insulation of joints - Inspection - Connections to existing structure or pipe(s) - Backfilling	- Survey and layout - Equipment(s) move in - Site preparation - Disposal of excavation - Removing old pipe(s) - Safety end treatment - Pipe testing

Work Item Level PRODUCTIVITY FACTOR		**Diameter of Pipe (18", 21", 30", 36", 42"), (*Note*;________________________________)** **Connection to Existing Structure or Pipes (Yes, No), (*Note*;________________________)** **No. of Inlet & Manhole in the section (Specify;__________________________________)`** **Approximate Trench Depth (*Specify*;_______________________________________)** **Any Utility Conflict (None, Low, Average, High), (*Note*;___________________________)** **No. of Inlet & Manhole in the section (Specify;__________________________________)** **No. of Inlet & Manhole installed during observation period (Specify;________________)** **No. of Pipe line (Single, Double), (*Note*;____)**
		- Soil Type / Water Table Depth
NODE	**Starting**	- Excavation or Completion of Stacking, whichever comes first.
	Ending	Backfilling is completed as indicated on the plans. A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.
STANDARD RESOURCE		- Labor: One Crew(4-5) - Equipment: One Back-hoe, One Crain(or another Back-hoe)
		Comment ; **Verified ________**

Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.

APPENDIX G. WORK ITEM SHEETS (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	**RC Pipe, Over 72"**	**464-3**	**LF/ Std. Res. Day**

<table>
<tr><th>SCOPE</th><th>Included</th><th colspan="2">Not Included</th></tr>
<tr><td colspan="2">- Excavation and dewatering
- Trench excavation protection work
- Shaping and bedding
- Pipe Handling from storage yard
- Laying pipe
- Joining and insulation of joints
- Inspection
- Connections to existing structure or pipe(s)
- Backfilling</td><td colspan="2">- Survey and layout
- Equipment(s) move in
- Site preparation
- Disposal of excavation
- Removing old pipe(s)
- Safety end treatment
- Pipe testing</td></tr>
<tr><td colspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">Diameter of Pipe (18", 21", 30", 36", 42"), (Note;________________________________)
Connection to Existing Structure or Pipes (Yes, No), (Note;________________________)
No. of Inlet & Manhole in the section (Specify;__________________________________)`
Approximate Trench Depth (Specify;____)
Any Utility Conflict (None, Low, Average, High), (Note;___________________________)
No. of Inlet & Manhole in the section (Specify;__________________________________)
No. of Inlet & Manhole installed during observation period (Specify;________________)
No. of Pipe line (Single, Double), (Note;____)
- Soil Type / Water Table Depth</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Excavation or Completion of Stacking, whichever comes first.</td></tr>
<tr><td>Ending</td><td colspan="2">- Backfilling is completed as indicated on the plans.
- A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.</td></tr>
<tr><td colspan="2">STANDARD RESOURCE</td><td colspan="2">- Labor: One Crew(4-5)
- Equipment: One Back-hoe, One Crain(or another Back-hoe)
Comment ;
Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

APPENDIX G. WORK ITEM SHEETS (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Concrete Box Culvert	**Precast**	**462**	**LF/ Std. Res. Day**

SCOPE	**Included**	**Not Included**
	- Excavation and dewatering - Excavation protection work - Shaping and bedding - Box handling from storage yard to Work Zone - Laying box covert - Joining and insulation of joints - Connections to existing structure(s) - Inspection - Backfilling	- Equipment(s) move in - Site preparation - Disposal of excavation - Box testing - Storage and shipment of box - Removal of old structure - Safety end treatment - Wingwall work
Work Item Level PRODUCTIVITY FACTOR	**Sizes (*Specify;* ____)** **Connection to Existing Structure or Pipes (Yes, No), (*Note*;________________________)** **Approximate Trench Depth (*Specify*;____)** **Any Utility Conflict (None, Low, Average, High), (*Note*;__________________________)** **No. of line (Single, Double), (*Note*;____)** - **Soil type / Water table depth**	
NODE — **Starting**	- Excavation or Completion of Stacking , whichever comes first.	
NODE — **Ending**	- Backfilling is completed as indicated on the plans. - A minimum of compacted fill has been placed over the box covert, if permanent backfill is not scheduled shortly.	
STANDARD RESOURCE	- Labor: One Crew(5-7) - Equipment: One Back-hoe, One Crain (or another Back-hoe) **Comment ;** **Verified ________**	

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix G. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th colspan="2">Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Inlets and Risers</td><td colspan="2">Limit to extensions of existing Inlets/Risers in Drainage Line</td><td>465</td><td>EA/Crew Day(s)</td></tr>
<tr><td>SCOPE</td><td colspan="3">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="4">- Excavation and dewatering
- Trench excavation protection work
- Shaping and bedding
- Concrete Handling and drying, formwork and rebar placing (if CIP)
- Placing precast units (if precast)
- Installation of joints
- Inspection
- Connections to existing structure or pipe(s)</td><td colspan="2">- Survey and layout
- Site preparation
- Mobilization and setting up of equipment(s)
- Disposal of excavation
- Removing old pipe(s)
- Testing and functionality check(s)
- Backfilling
- (Limit to Stage 1 : Extension)</td></tr>
<tr><td colspan="2" rowspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="4">Dimension of Inlets/Risers (Specify: ____)
Approximate Depth (Specify; ____)
Item(s) measured: Inlets (Details: ____)
Item(s) measured: No. ____________ Inlets)
Select types: CIP Inlets/Precast Inlets/CIP Manholes/Precast manholes
Select crew(s) type: Same crew/ Different Crews, for concreting, formwork and excavation</td></tr>
<tr><td colspan="4">- Water table depth / Soil type</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="4">- False work or Excavation, whichever starts first.</td></tr>
<tr><td>Ending</td><td colspan="4">- Concrete placement is completed.</td></tr>
<tr><td colspan="2">STANDARD RESOURCE</td><td colspan="4">Comment ;
Verified _______</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix G. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Manholes	**Limit to extensions of existing M/H in Drainage Line**	**465**	**Crew Day(s)/EA**

SCOPE	**Included**	**Not Included**
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Concrete Handling and drying, formwork and rebar placing (if CIP) - Placing precast units (if precast) - Installation of joints - Inspection	- Survey and layout - Site preparation - Mobilization and setting up of equipment(s) - Disposal of excavation - Removing old pipe(s) - Testing and functionality check(s) - Backfilling - (Limit to Stage 1 : Extension)

Work Item Level PRODUCTIVITY FACTOR		**Dimension of Inlets/Risers (Specify: ____)** **Approximate Depth (Specify; ____)** **Item(s) measured: Inlets (Details: ____)** **Item(s) measured: No. _____________ Inlets)** **Select types: CIP Inlets/Precast Inlets/CIP Manholes/Precast manholes** **Select crew(s) type: Same crew/ Different Crews, for concreting, formwork and excavation** - Water table depth / Soil type
NODE	**Starting**	- False work or Excavation, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		**Comment ;** **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix G. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Head-Wall/Wing-wall	**CIP**	**466**	**Crew Days / EA**

SCOPE	Included	Not Included
	- False work - Installation of forms and rebar - Inspection of forms and rebar - Handling and placing of concrete - Apron	- Site preparation - Preparation of rebar and forms - Rebar fabrication - All necessary work for the protection of concrete placed under any weather conditions - Curing - Removal of forms - Surface finishing - Installation of drainage pipe - Removal of false work - Precast Concrete Panel - Safety Covers / Safety End Treatment - Base preparation (fine grade and seal slab)

Work Item Level PRODUCTIVITY FACTOR		**Approximate dimension (W*H :_______________), (*Note;* _____________________)** **Thickness of wall (*Specify;* ____)** **Apron (Yes: ___________SF, No), (*Note;*___________________________________)**
NODE	**Starting**	- False work or form work, whichever starts first.
	Ending	- Concrete placement is completed.
A Crew Definition		- Labor: One Crew for Formwork(4-5), One Crew for Rebar installation(4-5) **Comment ;** **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

APPENDIX H: SAFETY PROTOCOL

Safety Protocol

Safety Protocol for Construction Site Visits

(TXDOT Project 0-4416)
READ, FAMILIZE and OBEY THIS SAFETY PROTOCOL BEFORE SITE VISIT

Ensure compliance with all regulations concerning the standard safety procedures of TxDOT and site.

Site protocol

Arrival: On each and every visit, the GRA must report to field office and gain permission to enter the site.

Departure: Report back to the field office on departure.

Vacant Sites: If there are no site representatives on site, then access is prohibited.

Instructions: GRA must follow any instructions given to them whilst on site, from the site representative or TxDOT personnel.

Safety Procedures

Responsibility
Avoiding accidents: GRA can avoid accidents by concentrating and thinking before acting. Remember that acting on impulse and taking shortcuts causes many accidents.

Parking & Transportation: GRA should park near the field office and go to job site with TxDOT personnel.

Clothing
Safety vest: Wear safety vest all the times in the job site.

Hardhats: Wear safety hardhats all the times in the job site.

Footwear: Wear steel-toed boots if required.

Appendix H Safety Protocol (Cont'd)

Hearing protection: Ear protection should be worn if required.

Safety glass: Wear safety glass in required area.

Loose clothing: Do not wear loose clothing.

Moving around the site

Barricades: Do not lean over or go beyond any protective handrails or barricades.

Openings: Be careful where you walk. Pay attention to openings, barriers, protective covers and changes in levels.

Access: Use correct access at all times.

Restricted areas: Keep out of restricted areas.

Movement: Running on any part of the site is prohibited. Never walk backwards in a construction area. Do not jump from equipment, platforms or scaffolds. Do not stand or walk under any loads being lifted.

Weather: Beware of slippery surfaces (particularly after or during rain). Be careful in windy weather.

Behaviors on-site: Restrict communication with workers unless it is necessary for the research.

Traffic: Be aware of moving equipment and vehicles. Traffic rules should be obeyed and strict attention should be paid to all warning signs at all times.

Taking pictures: GRA can freely take the pictures on the surveyed Work Items unless it is restricted.

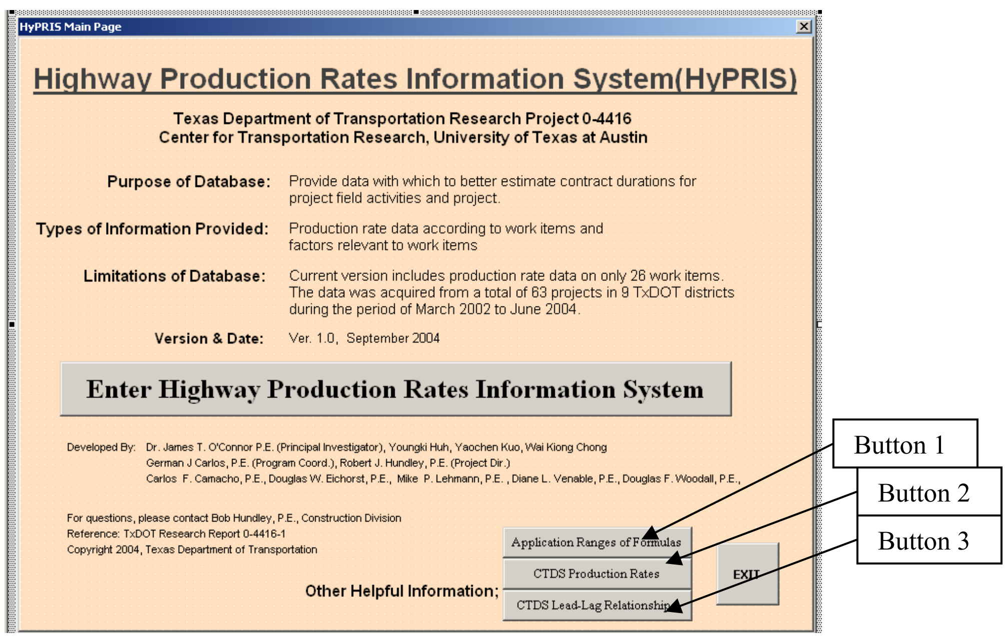
APPENDIX I: MANUAL FOR USING HYRPIS

Manual for Using HyPRIS

1. Before opening the file, set your computer Macro Security to "Medium". Go to "Tools", choose "Options" and go to "Security". Click on "Macro Security" and set to "Medium"

2. Open the file. The window will prompt you whether you want to "Enable" or "Disable" Macro. Click on the "Enable Macro" button. All "active" buttons are in grey and have bolded wordings.

3. The window for the system will appear as below:



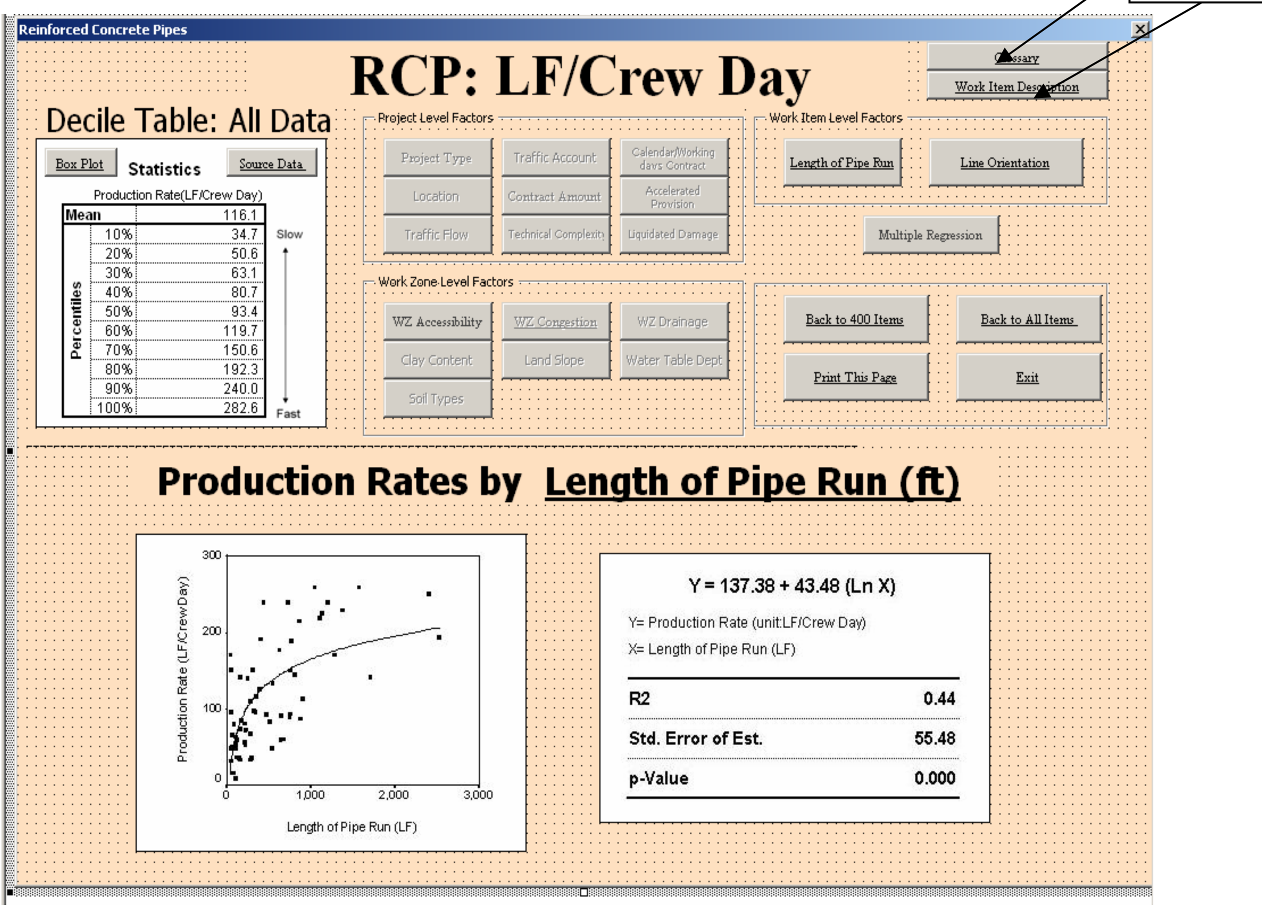
4. One can surf around the system the way one surfs the internet.

5. One can start proceed to rate information by pressing the button "Enter Highway Production Rate Information System".

6. Other helpful information provided in this window:

7. Application Range of Formulas: As shown in the first HyPRIS window. It advises users of the production rate range whereby associated formulae are applicable. (see button 1).
8. CTDS Production Rates: It provides the Production Rates from the previous system and users can access CTDS production rates to estimate work items which this system does not have (see button 2).
9. CTDS Lead-Lag Relationships: It provides information on the Lead-Lag Relationships that were developed by others for the CTDS (see button 3).
10. Information is arranged according to Work Item numbers listed in the TxDOT Specifications (2004).

Typical Work Item Window



11. Glossary: It provides definitions for the statistical terms and other terminology used to describe the factors for various work items (Button 4).

12. Work Item Description: It displays the scope of activity and resources for the work item (Button 5).

13. To make sure that the Printing Output functions correctly, users are to set the printer to "Landscape" paper orientation in the Printer Option of the Control Panel.

APPENDIX J: MANUAL FOR UPDATING HYPRIS

Manual for Updating HyPRIS

The system uses Microsoft Visual Basic as its software language. Those updating the system should be familiar with the language of the program and methods to activate and deactivate buttons on the program.

Those adding or modifying production rate information should also be familiar with SPSS.

Procedures related to adopted for different information/elements:

Scattered Plots: On the SPSS “Output Screen”, first, convert the file to the required format using the SPSS chart editor and drop down manual “Format: Apply Chart Template”, use the format titled “Box plot for DB” from CD the provided, next, set the graphic to 65% and save as “Chart”.

Box Plots: On the SPSS “Output Screen”, first, convert the file to the required format using the SPSS chart editor and drop down manual “Format: Apply Chart Template”, use the format titled “scatter plot_dbp” from CD the provided, next, set the graphic to 65% and save as “Chart”.

Datapoints Sources and Information Tables: Open the excel file “Input for Database”, search for the worksheet “DP”, key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 395, height 350

Decile Tables: : Open the excel file “Input for Database”, search for the worksheet “Regression Table”, key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 295, height 196.

Regression Formulas and Statistics: Open the excel file “Input for Database”, search for the worksheet “Regression Table”, key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 295, height 196.

Multiple Regression Formulas and Statistics: Open the excel file “Input for Database”, search for the worksheet “Multiple Regression”, key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 420, height 200.

Glossary Table: Enter information into the word file “Glossary of Terms (Final)” and arranged according the alphabetical order. Convert the entire information into jpeg file.   All inputs into the system are in jpeg format.

APPENDIX K: SURVEY ON CTDS USAGE AND IMPORTANCE

Survey on Contract Time Determination System Usage and Importance

Distr.	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
ABL	0%	N/A	The District Engineer has mandated that all project construction time estimates be developed in this district using Suretrak.	No	100%
AMA	0%	N/A	We do not use CTDS. We have developed Road Const Production Rates based on the last 5 yrs const reports. We use these production rates in Primavera to establish the const working days schedule. The only time we use CTDS is to look at production rates which we do not have established in our const records for our Road Const Production Rates.		100%
ATL	0%	Same		No	10%
AUS	20%	Same		No	5%
BMT	100%	Same		No	0%
BWD	30%	Same	The CTDS system is not easily adapted. The projects we deal with do not normally fit the projects that CTDS has preset in its program. It is hard to remove or alter items on the list for a particular type of project. It is not easy to change or correct mistakes. Units for items should be changeable. Only a certain number of basic items should be preset with other items that can be optional. CTDS does address Lighting or Electrical type items very well. The CTDS program should be able to link to estimator, so items do not have to be entered more than once.	Yes	5-10%
BRY	25%	Less	We have no opinions. Our district does not use the CTDS system (excel spreadsheet). Our consultants use the CTDS system 100% of the time unless a CPM is required.		
CHS	0%	N/A	We are having a districtwide training on CPM in Nov. Once that is complete, we plan on utilizing it to estimate const time.		0%
CRP					

APPENDIX K SURVEY ON CONTRACT TIME DETERMINATION SYSTEM USAGE AND IMPROVEMENT (Cont'd)

Distr.	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
DAL	5%	Less	A. System Program needs updating from Lotus to Excel. B. We prefer a program with popup menus that give the options of Project Types, Daily Prod Rates for Standard Work Items and Base Production rates and Sensitivity Factors. C. Currently we are using an Excel sheet with formulas that include the data tables provided by the AC No. 17-93.	Yes	5%
	10%	Less	1. This program is not user friendly. 2. Without some sort of back-calculation, the contract time generated is unrealistic. 3. Daily production rate table does not make any sense for small projects such as CMAQ. 4. Some of the % complete of the preceding activity needs to be thoroughly reviewed.	Yes	50%
	95%	Same	No	No	0%
	100%	Same	1. Increase production rate or have a more accurate production rate. 2. Allow accelerated construction 3. Include Project Scheduling sheet	No	0%
ELP	25%	Same	We used to use CTDS a lot more before, but now we use "Suretrak" and "Primavera". Overall, we use CTDS for smaller projects.	Yes	75%
FTW	100%	Same	The daily production rates are unrealistic for the FTW district. The district has come up with rates that fit our conditions and contractors. System could be improved by setting production rates for each district.	No	0%
LRD					
LBB	0%	N/A	N/A	No	100%

APPENDIX K SURVEY ON CONTRACT TIME DETERMINATION SYSTEM USAGE AND IMPROVEMENT (Cont'd)

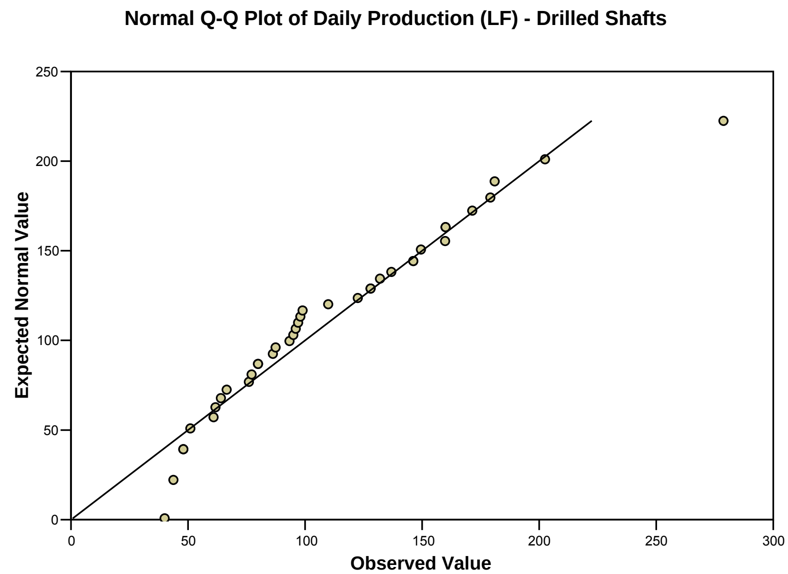
Distr.	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
LFK	5%		To be useful the production rates need to be more representative of specific size of job and region of state. Also since our district has switched to calendar days on all projects a system based solely on production rate is not very useful. We are trying to implement the use of Suretrak. We would rather have help with creating calendars, production rates and critical path relationships for the newer methods and programs.	No	95%
ODA	0%	N/A	We have not been using the program since 1997 when it was being supported by CST. Any versions of CTDS that run in excel have not been provided to us.	Yes	0%
PAR					
PHR	100%	Less	We are currently in the process of switching to 100% use of SureTrak to calculate all our contract time.	Yes	100%
	0%	N/A	I have never used the CTDS system, nor has anyone else in my office. Therefore, I cannot give any suggestions for improvement.	No	100%
	5%	Same	No comments on CTDS specifically, however as more of a question, are there any updated rates on the work items using actual pay item units? Such as linear feet for drill shafts instead of CY, etc? Or for that matter anywhere we can look to see a set of the rates from our district compiled from past construction projects?	No	95%
SJT	0%	N/A	The SJT district follows the procedure detailed in TxDOT circular 17-93 for the determination of contract time. We have not implemented CTDS.	No	80%
	0%	N/A	We do not currently use CTDS. We are using Primavera to estimate contract time.		100%
YKM	0%	N/A	Yoakum TxDOT projects are simpler to do by hand because of their small size. We do use Excel in some/most cases.	Yes	0%

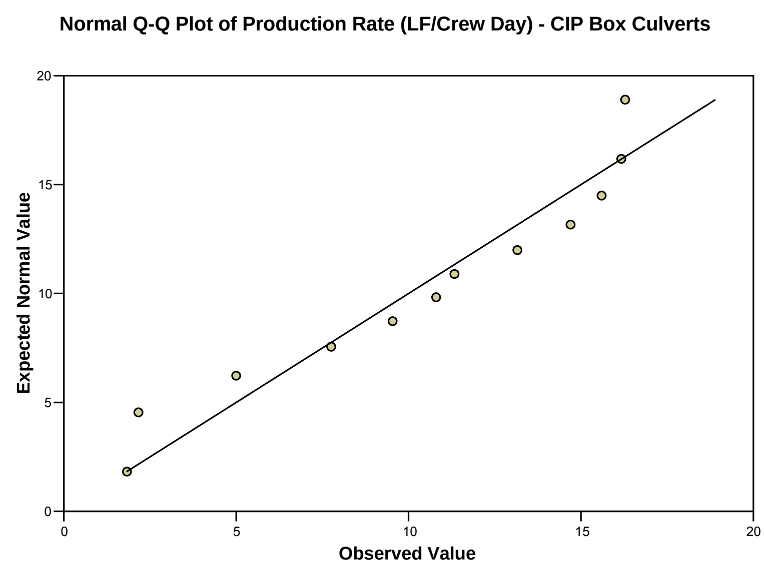
APPENDIX K SURVEY ON CONTRACT TIME DETERMINATION SYSTEM USAGE AND IMPROVEMENT (Cont'd)

Distr.	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
SAT	<5%	Less	We are using CPM software more and more, even on small projects that do not require CPM usage. Designers are still using the daily production rates from the CTDS system to calculate task completion in days, but this only covers certain tasks and some are blanket tasks. We are not sure if improving the CTDS system is the answer. We would suggest that daily production rates be analyzed using current construction industry practices and standards. Also, new tasks and breaking up some blanket tasks should be done to cover more of the incidentals associated with construction projects and how they affect time determination. Also, a more uniform approach to setting up calendars in CPM generated schedules. This may involve using historical data from construction projects on actual number of days worked per month for a year.	No	95%
	0%	N/A	I have never used the CTDS system, nor has anyone else in my office. Therefore, I cannot give any suggestions for improvement.	No	100%
	5%	Same	No comments on CTDS specifically, however as more of a question, are there any updated rates on the work items using actual pay item units? Such as linear feet for drill shafts instead of CY, etc? Or for that matter anywhere we can look to see a set of the rates from our district compiled from past construction projects?	No	95%
WFS	0%	N/A	We do not currently use CTDS in WFS district simply because we not know what it is. We continue to develop our project const time estimates by preparing worksheets in accordance with the directives by AC 17-93. We may be missing out on a great opportunity, but we are currently completely unaware of the details, abilities, drawbacks or benefits of this system. Therefore, it is impossible to provide any other input to questions 2 and 4. We would love to hear more about CTDS.	N/A	0%
TYL	15%	Same	The main concern the designers have is the rate of production. Each Area Office has a general idea of the rates that their contractors use in their schedule submissions but this information is rarely consistent with actual field rates. We would request that a data base of actual field production rates be developed to be provided to designers.		

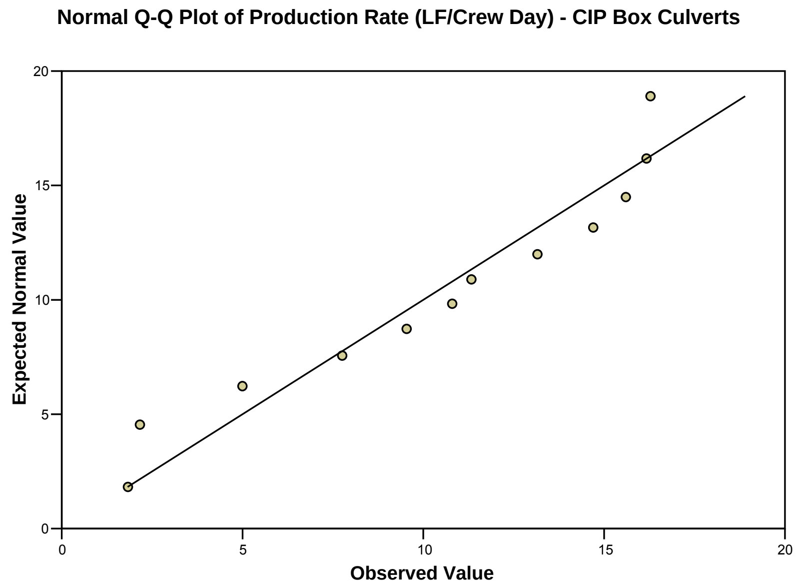
APPENDIX L: Q-Q PLOT FOR DATA POINTS

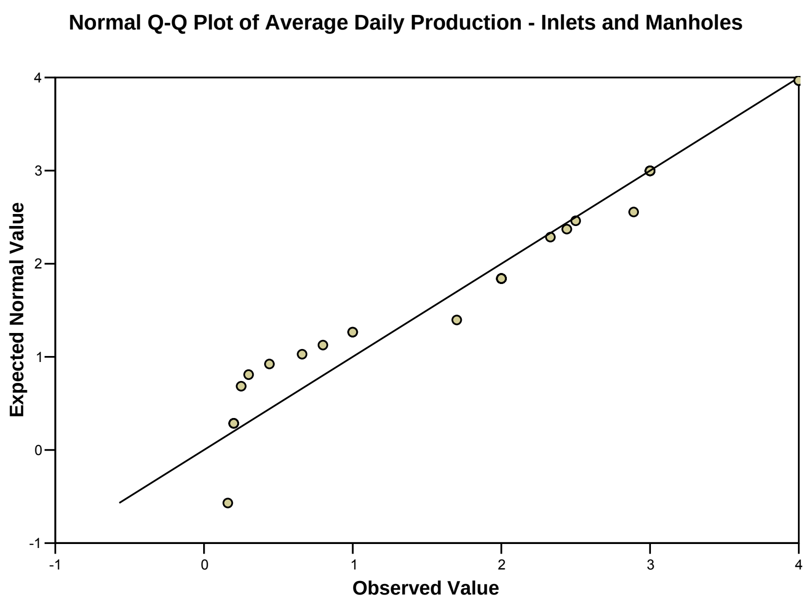
Q-Q Plot for Data points



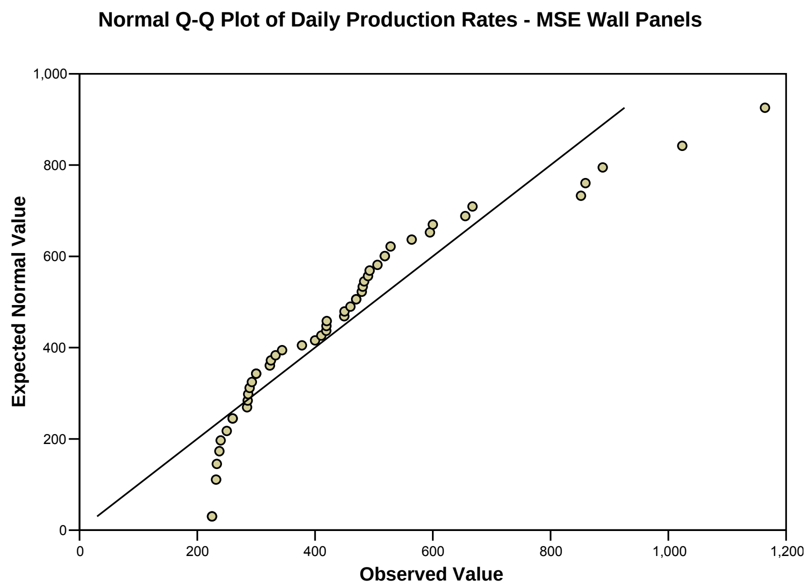


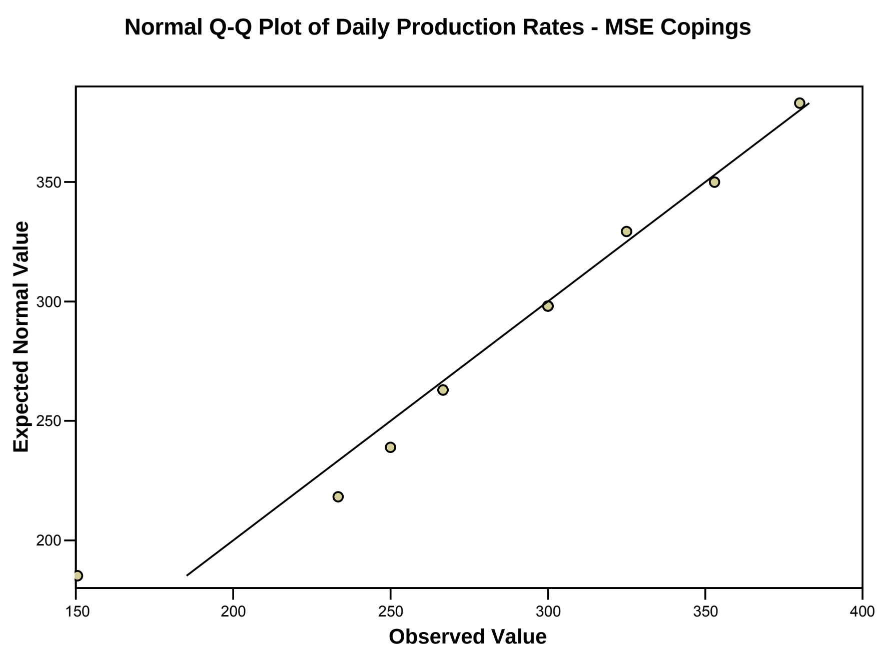
Appendix L: Q-Q Plot for Data points (Con't)





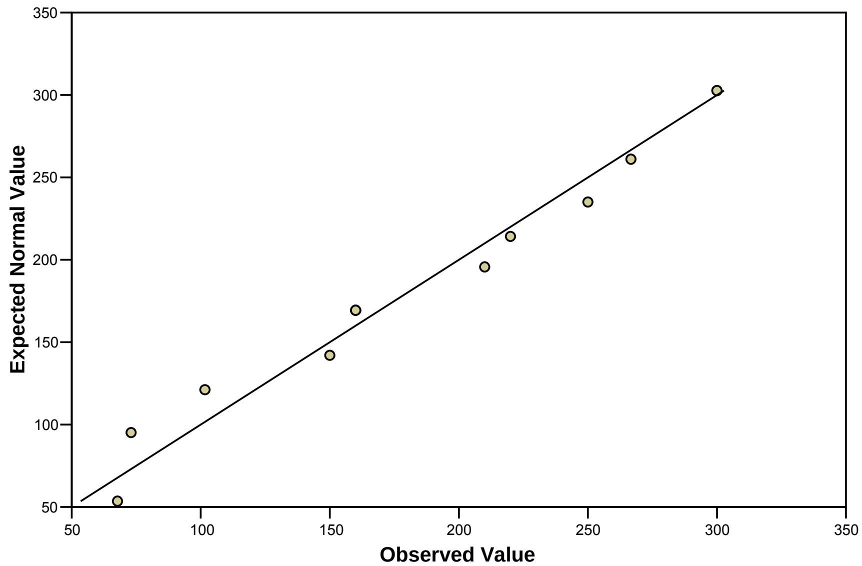
Appendix L: Q-Q Plot for Data points (Con't)



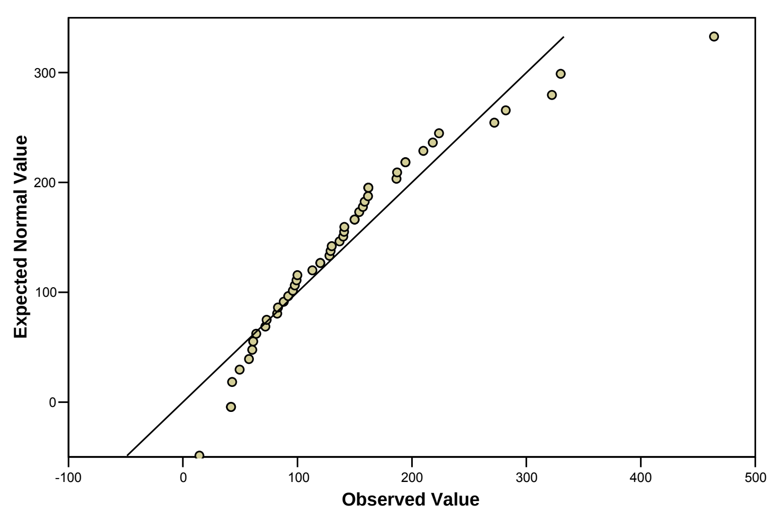


Appendix L: Q-Q Plot for Data points (Con't)

Normal Q-Q Plot of Daily Production Rates - MSE Leveling Pads and Footings

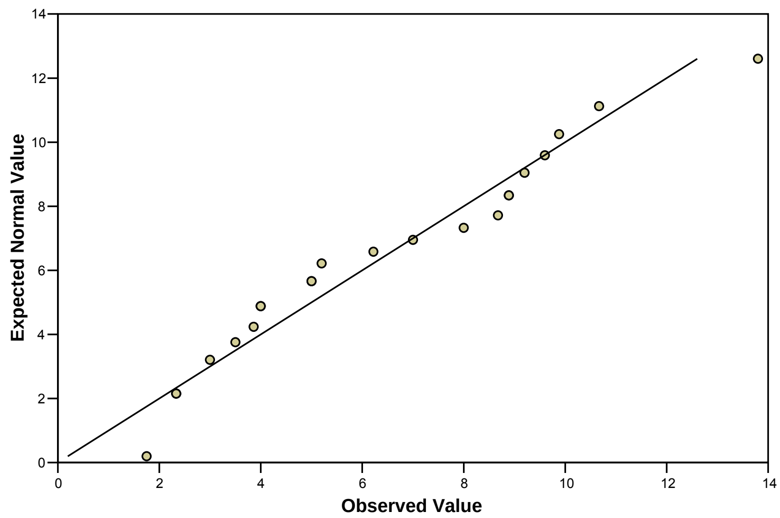


Normal Q-Q Plot of Production Rate (LF/Day) - PC Box Culverts

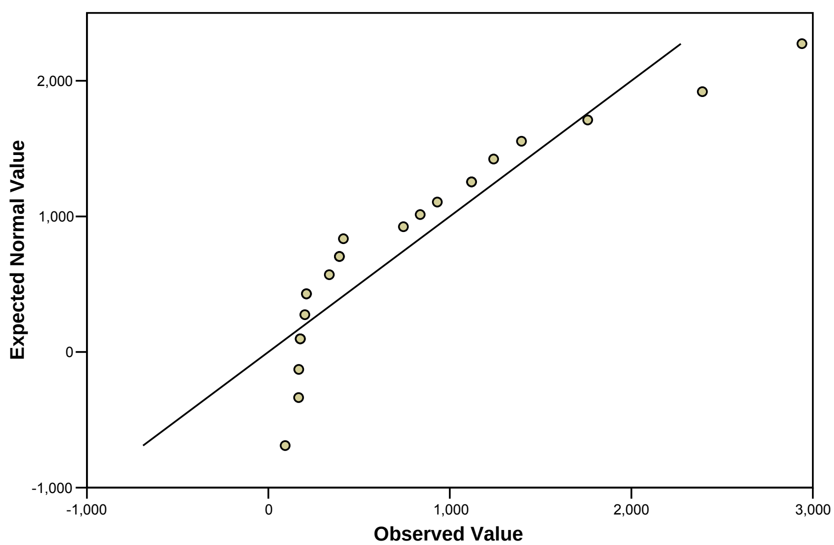


Appendix L: Q-Q Plot for Data points (Con't)

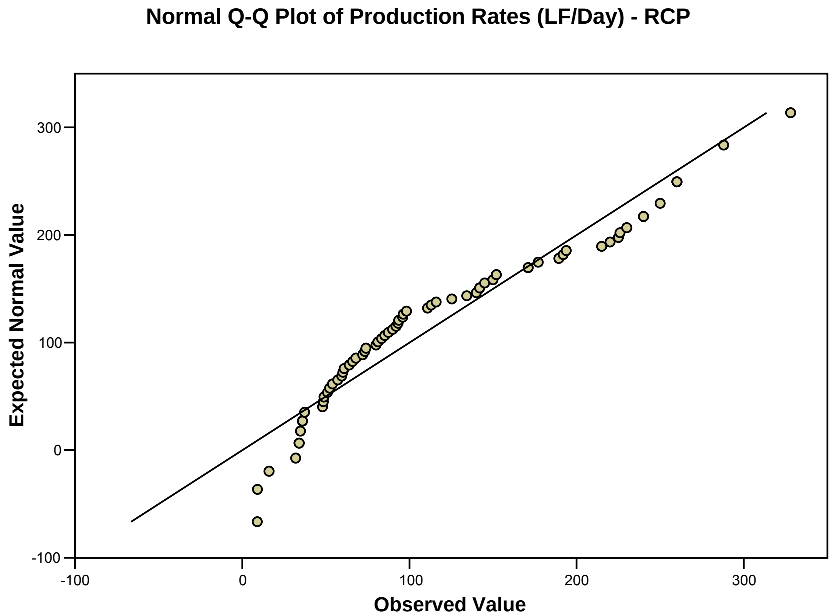
Normal Q-Q Plot of Daily Production (EA/Day) - Piling Foundations

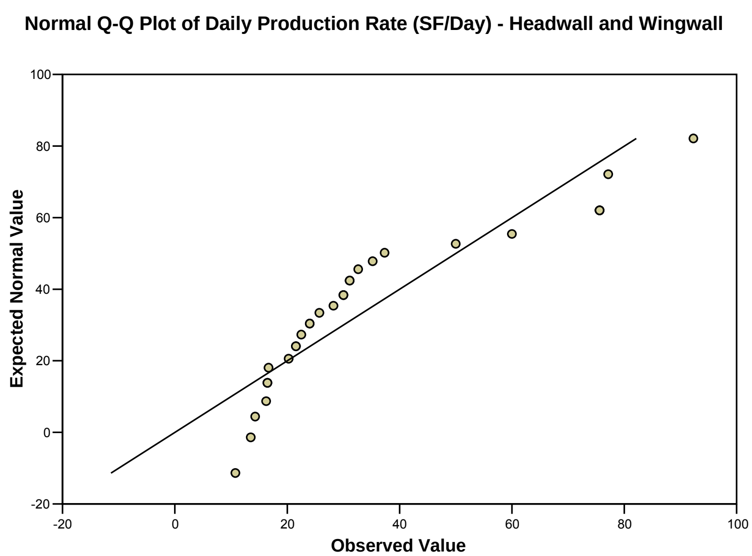


Normal Q-Q Plot of Daily Production (LF/Day) - Piling Foundations



Appendix L: Q-Q Plot for Data points (Con't)





References

Abdelhamid, T. S., and Everett, J. G. (1999). “Time Series Analysis for Construction Productivity Experiments.” *J. Constr. Engrg.and Mgmt*., ASCE, 125(2), 87-95.

AbouRizk, S., Knowles, P., and Hermann, U. R. (2001). “Estimating Labor Production Rates For Industrial Construction Activities.” *J. Constr. Engrg. and Mgmt*., ASCE, 127(6), 502-511.

Albright, S. C., Winston, W. L., and Zappe, C. (1999). *Data Analysis & Decision Making*. Pacific Grove, CA.

Allmon, E., Haas, C. T., Borcherding, J. D., and Goodrum, P. M. (2000). “U.S. Construction Labor Productivity Trends, 1970–1998.” *J. Constr. Engrg. and Mgmt*., ASCE, 126(1), 97-104.

Allouche, Erez N., Ariaratnam, Samuel T. and AbouRizk, Simon M. (2001), Application of Horizontal Characterization Techniques in Trenchless Construction, Journal of Construction Engineering and Management, 127(6), 476-484

Bubshait, A. A. and Cunningham, M. J. (1998). Comparison of Delay Analysis Methodologies, *Journal of Construction Engineering and Management*, 124 (315), pp 60 – 65.

Borcherding, J. D. (1976). “Improving Productivity in Industrial Construction.” *Journal of Construction Devision*, ASCE, 102(CO4), 599-614.

Borcherding, J. D., and Alarcon, L. F. (1991). “Quantitative Effects on Construction Productivity.” *The Construction Lawyer*, American Bar Association, 11(1), 35-48.

Borcherding, J. D., and Garner, D. F. (1981). “Work Force Motivation and Productivity on Large Projects.” *Journal of Construction Division*, ASCE, 107(CO3), 443-453.

Borcherding, J. D., and Oglesby, C. H. (1974). “Construction Productivity and Job Satisfaction.” *Journal of the Construction Division*, ASCE, 100(CO3), 413-431.

Borcherding, J. D., Sebastian, S. J., and Samelson, N. M. (1980). "Improving Motivation and Productivity on Large Projects." *Journal of the Construction Division*, ASCE, 106(CO1), 73-89.

Bhurisith, L., and Touran, A. (2002). "Case Study of Obosolescence and Equipment Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 128(4), 357-361.

The Business Roundtable (1980). "Scheduled Overtime Effect on Construction Project." *Construction Industry Cost Effectiveness Task Force Report*, November.

The Business Roundtable (1982). "Measuring Productivity in Construction." *Report A-1*, September.

Chambers, J., Cleveland, W., Kleiner, B., and Tukey, P. (1983). *Graphical Methods for Data Analysis*. Wadsworth.

Chang. L. M., and Borcherding, J. D. (1986). "Craftsman Questionnaire Sampling." *J. Constr. Engrg. and Mgmt*., ASCE, 112(4), 543-556.

Cho, S. (2000). "Development of the Project Definition Rating Index (PDRI) for Building Projects." *Doctoral Dissertation*, The University of Texas at Austin, Austin, TX, May 2000.

Christian J., and Hachey D. (1995). "Effects of Delay Times on Production Rates in Construction." *J. Constr. Engrg. and Mgmt*., ASCE, 121(1), 20-26.

Christian J., and Hachey D. (1996). "A Computer-aided System to Improve Production Rates in Construction." *Advances in Engineering Software*., V. 25, 207-213.

The Construction Industry Institute (1988). "The Effects of Scheduled Overtime and Shift Schedule on Construction Craft Productivity." Construction Industry Institute, The University of Texas at Austin.

The Construction Industry Institute (1990). "Productivity Measurement: An Introduction." Construction Industry Institute, The University of Texas at Austin.

El-Rayes, K., and Moselhi, O. (2001). "Impact of Rainfall On the Productivity of Highway Construction." *J. Constr. Engrg. and Mgmt*., ASCE, 127(2), 125-131.

Gidado, K. I. (1996). “Project Complexity: The Focal Point of Construction Production Planning.” *J. Construction Management and Economics*, V.14, 213-225.

Goodrum, P. M. (2001). “The Impact of Equipment Technology on Productivity in the U.S. Construction Industry.” *Doctoral Dissertation*, The University of Texas at Austin, Austin, TX, May 2001.

Goodrum, P. M., and Haas, C. T. (2002). “Partial Factor Productivity and Equipment Technology Change at Activity Level in U.S. Construction Industry.” *J. Constr. Engrg. and Mgmt*., ASCE, 128(6), 463-472.

Gransberg, D. D. (1996). “Optimizing Haul Unit Size and Number Based on Loading Facility Characteristics.” *J. Constr. Engrg. and Mgmt*., ASCE, 122(3), 248-253.

Green, S. B. (1991). “How Many Subjects Does It Take to Do A Regression Analysis?” *Multivariate Behavioral Research*, Lawrence Erlbaum Associates, 26(3), 499-510.

Guo, Sy-Jye (2002), “Identification and Resolution of Work Space Conflicts in Building Construction”, *J. Constr. Engrg. and Mgmt*., ASCE, 128(4), 287-295.

Grimm, C. T., and Wagner, N. K. (1974). “Weather Effects on Mason Productivity.” *Journal of Construction Division*, ASCE, 100(3), 319-335.

Hancher, D. E., McFarland, W. F., and Alabay, R. T. (1992) “Construction Contract Time Determination” Texas Department of Transportation Research Report.

Halligan, D. W., Demsetz, L. A., and Brown, J. D. (1994). “Action-Response Model and Loss of Productivity in Construction.” *J. Constr. Engrg. and Mgmt*., ASCE, 120(1), 47-64.

Hanna, A. S., Camlic, R., Peterson P. A., and Nordheim, E. V. (2002). “Quantitative Definition of Projects Impacted by Change Orders.” *J. Constr. Engrg. and Mgmt*., ASCE, 128(1), 57-64.

Hendrickson, C., Martinelli, D., and Rehak, D. (1987). “Hierarchical Rule-based Activity Duration Estimation.” *J. Constr. Engrg. and Mgmt*., ASCE, 113(2), 288-301.

Herbsman, Z. J., and Ellis, R. (1995). “Determination of Contract Time for Highway Construction Projects.” *National Cooperative Highway Research Program Synthesis of Highway Practice 215, Transportation Research Board,* National Research Council, Washington, DC (October), 43PP.

Jiang, Y. (2003). “The Effects of Traffic Flow Rates at Freeway Work Zones on Asphalt Pavement Construction Productivity.” *Transportation Quarterly*, V.57, n.3, Summer, P83-103.

Jonasson, S., Dunston, P. S., Ahmed, K., and Hamilton, J. (2002). “Factors in Productivity and Unit Cost for Advanced Machine Guidance.” *J. Constr. Engrg. and Mgmt*., ASCE, 128(5), 367-374.

Kaming, Peter F., Olomolaiye, Paul O., Holt, Gary D. and Harris, Frank C. (1997), “Factors influencing construction time and cost overruns on high-rise projects in Indonesia”, *Construction Management and Economics,* 15 (1), 83-94.

Kartam, Saied (1999). Generic Methodology for Analyzing Delay Claims, *Journal of Construction Engineering and Management,* 125(409), pp 411 – 419.

Koehn, E., and Brown, G. (1985). “Climatic Effects on Construction.” *Journal of Construction Engineering and Management,* ASCE, 111(2), 129-137.

Koehn, E., and Ahmed, F. (2001). “Production Rates for Urban/Rural Projects in Developing Areas” *International Transaction*, AACE, INT.03, 01-06.

Lee, E.-B., Lobbs, C. W., Harvey, J. T., and Roesler, J. R. (2000). “Construction Productivity and Constraints for Concrete Pavement Rehabilitation in Urban Corridors.” *Transportation Research Record*, n.1712, P13-22.

Leu, Sou-Sen & Hwang, Shao-Ting (2001), Optimal Repetitive Scheduling Model with Shareable Resource Constraint, *J. Constr. Engrg. and Mgmt*., ASCE, 127(4), 90-103.

Liou, F. S., and Borcherding, J. D. (1986). “Work sampling Can Predict Unit Rate Productivity.” *J. Constr. Engrg. and Mgmt*., ASCE, 112(1), 90-103.

Majid, M. Z. Abd. and McCaffer, R (1998). Factors of Non-Excusable Delays That Influence Contractors' Performance, *Journal of Management in Engineering,* 14(42), pp 42-49.

Marzouk, M., and Moselhi, O. (2003). "Object-oriented Simulation Model for Earthmoving Operations." *J. Constr. Engrg. and Mgmt*., ASCE, 129(2), 173-181.

Murawski, Ronald Stephen (2001), "Analysis of Construction Production Rates Using the Work Breakdown Structure System", Master Thesis, The University of Texas at Arlington.

National Cooperative Highway Research Program Synthesis of Highway Practice 79. (1981). "Contract Time Determination." *Transportation Research Board,* National Research Council, Washington, DC (October), 45PP.

National Electrical Contractors Association. (1974). "The Effect of Temperature on Productivity." *Test Report*, Washington, DC.

Noyce, David A. and Hanna, Awad S. (1998), "Planned and unplanned schedule compression: The impact on labour", *Construction Management and Economics,* Vol. 16, 479-490.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). *Productivity improvement in construction.* McGraw-Hill Publishing Inc., New York, NY.

Ovararin, N., and Popescu, C. M. (2001). "Field Factors Affecting Masonry Productivity." *International Transaction*, AACE, EST-09.

Peurifoy, R. L., and Schexnayder, C. J. (2002). C*onstruction Planning, Equipment, and Methods. 6th Edition,* McGraw-Hill Publishing Inc., New York, NY.

Poh, Paul S.H. and Chen, Jundong (1998), "The Singapore buildable design appraisal system: a preliminary review of the relationship between buildability, site productivity and cost", *Construction Management and Economics*, Vol. 16(6), 681-692.

Proverbs, G. D., Holt, G. D., and Olomolaiye, P. O. (1997). "European Construction Contractors: A Productivity Appraisal of in-situ Concrete Operations." *J. Construction Management and Economics*, V.17, 221-230.

Proverbs, G. D., Holt, G. D., and Olomolaiye, P. O. (1999). “Construction Resource/Method Factors influencing productivity for high rise concrete construction.” *J. Construction Management and Economics*, V.17, 577-587

R.S. Means Company, Inc. (2002). *R.S. Means Heavy Construction Cost Data*, 59th Annual Edition, *R.S. Means Company, Inc*., Kingston, MA.

Sanders, S. R., and Thomas, H. R. (1991). “Factors Affecting Masonry-Labor Productivity.” *J. Constr. Engrg. and Mgmt*., ASCE, 117(4), 626-644.

Sanders, S. R., and Thomas, H. R. (1993). “Masonry Productivity Forecasting Model.” *J. Constr. Engrg. and Mgmt*., ASCE, 119(1), 163-179.

Sawhney, Anil, and Mund, Andre (2002), “Adaptive Probabilistic Neural Network-based Crane Type Selection System”, *J. Constr. Engrg. and Mgmt*., ASCE, 128(3), 265-273

Schexnayder, C., and Webber, S. L. (1999). “Effect of Truck Payload Weight on Production.” *J. Constr. Engrg. and Mgmt*., ASCE, 125(1), 1-7.

Shi, J. Jinsheng, Cheung, S.O. and Arditi, D. (2001). Construction Delay Computation Method, *Journal of Construction Engineering and Management*, 127 (60), pp 60 – 65.

Smith, S. D. (1999) “Earthmoving Productivity Estimation Using Linear Regression Techniques.” *J. Constr. Engrg. and Mgmt*., ASCE, 125(3), 133-141.

Smith, S. D., Wood, G. S., and Gould, M. (2000). “A New Earthworks Estimating Methodology.” *J. Construction Management and Economics*, V.18, 219-228.

Texas Department of Transportation (1993). “Standard Specifications for Construction of Highways, Streets and Bridges.” Texas.

Thomas, H. R. (1991). “Labor Productivity and Work Sampling: The Bottom Line.” *J. Constr. Engrg. and Mgmt*., ASCE, 117(3), 423-444.

Thomas, H. R. and Zavrski, I. (1999), Construction Baseline Productivity: Theory and Practice, *Journal of Construction Engineering and Management,* 125 (5), pp 295-303.

Thomas, H. R. (2000). "Schedule Acceleration, Work Flow, and Labor Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 126(4), 261-267.

Thomas, H. R., Mathews, C. T., and Ward, J. G. (1986). "Learning Curve Models of Construction Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 112(2), 245-258.

Thomas, H. R., Maloney, W. F., Horner, R. M. W., Smith, G. R., Handa, V. K., and Sanders, S. R. (1990). "Modeling Construction Labor Productivity" *J. Constr. Engrg. and Mgmt*., ASCE, 116(4), 705-726.

Thomas, H. R., and Raynar, K. A. (1997). "Schedules Overtime and Labor Productivity: Quantitative Analysis." *J. Constr. Engrg. and Mgmt*., ASCE, 123(2), 181-188.

Thomas, H. R., Riley, D. R., and Sanvido, V. E. (1998). "Loss of Labor Productivity Due to Delivery Methods and Weather." *J. Constr. Engrg. and Mgmt*., ASCE, 125(1), 39-46.

Thomas, H. R., and Yiakoumis I. (1987). "Factor Model of Construction Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 113(4), 623-639.

Thomas, H. R., and Završki, I. (1999). "Construction Baseline Productivity: Theory and Practice." *Journal of Construction Engineering and Management,* ASCE, 125(5), 295-303.

Tucker, R. L. et al. (1982). "Implementation of Foreman-Delay Surveys." *J. Construction Devision*, ASCE, 108(4), 577-591.

Wannacott, T. H., and Wannacott, R. J. (1987). *Regression: A Second Course in Statistics*. Malabar, FL.

Werkmeister, R. F., Luscher, B. L., and Hancher, D. E. (2000). "Kentucky Contract Time Determination System." *Transportation Research Record*, n.1712, P185-195.

Werkmeister, R. F., Luscher, B. L., and Hancher, D. E. (2000). "Kentucky Contract Time Determination System." *Transportation Research Record*, n.1712, P185-195.

Winch, G., and Carr, B. (2001). "Benchmarking on-site productivity in France and the UK: A CALIBRE Approach." *J. Construction Management and Economics*, V.19, 577-590.

Wideman, R. M. (1994). Applying Loading, Production & Learning Curves to Construction: A Pragmatic approach, *Canadian Journal of Civil Engineering,* 21 (9), pp 939-953.

VITA

Wai Kiong Chong was born in Singapore on July 20th, 1973. He is the youngest son of Yat Choy Chong (deceased) and Foong Chin (Agnes) Chin. He attended the National University of Singapore (NUS) in 1995 and graduated with a Bachelor of Science (Building) in 3.5 years in December 1998 and again with a Master of Science (Building) in June 2000.

He started working for the First Surveying of Shanghai as a Quantity Surveyor half a year before graduation in Shanghai, China. In 1999, he started another career with the Building and Construction Authority of Singapore as a Building Inspector/Researcher. He worked on a funded research project that looked at improving the Construction Quality Assessment System and automating several quality inspection systems. He made a big switch in his career by joining the Land Transportation Authority of Singapore as a Cost Control Engineer (Civil and Tunneling Division) and stayed on to complete three major sub-way and underground highway projects, totaling US$9.5 billion. He continued to work for the Land Transport Authority until he started his Ph.D. program at the University of Texas at Austin in August 2002.

Permanent Address: 6 Toh Yi Drive #10-251 Singapore 590006, Republic of Singapore

This Dissertation was typed by the author.